University of Southampton

Faculty of Environmental and Life Sciences

School of Geography and Environmental Science

Quantifying the Benefits of Natural Flood Management Methods in Groundwater-Dominated River Systems

by

Imogen C. Barnsley

Thesis for the degree of Doctor of Philosophy

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Abstract

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This thesis aims to address the gap in the Natural Flood Management (NFM) evidence base concerning its potential to reduce flooding in groundwater-dominated chalk catchments. Due to the difference in hydrological processes between groundwater-dominated chalk catchments and other typical UK river systems with a relative dominance of surface runoff, it is proposed that the flood reduction benefits of NFM in chalk catchments is currently unknown. A statistical approach is used to ascertain the likelihood of successful NFM implementation in 198 chalk catchments in England, by matching physical catchment properties hydrological characteristics with the associated NFM measures. Three catchment typologies were identified using redundancy analysis and hierarchical clustering: 1) large catchments, 2) headwater catchments with permeable soils, and 3) catchments with impermeable soils and surfaces. Based on the properties identified for Groups 1 and 2, it can be assumed that NFM will have limited flood reduction potential in these chalk catchments. Group 3 chalk catchments were identified as being most suitable to NFM based on catchment properties and hydrological processes. The findings of the statistical analysis were tested by taking an example Type 2 chalk stream, the River Test, and modelling in-channel NFM implementation and increasing landcover of deciduous woodland using the numerical model, SHETRAN. Model parameterisation of in-channel NFM scenarios are based on field-measured Manning's roughness values and the literature. Modelling results show that increasing tree cover, revegetating river channels, and installing large woody debris can generate a flood peak reduction averaging 5%. However, this 5% flood peak reduction does not translate to a reduction in flood duration, meaning that flooding in groundwater-dominated catchments will likely remain highly disruptive. The effectiveness of NFM under projected future climate change scenarios is tested by comparing NFM flood mitigation scenarios to a non-NFM baseline. Under future projected climate changes, NFM maintains its effect when compared to non-NFM baseline scenarios. This equates to an average 5% flood peak reduction and insignificant reductions in flood duration. All together these findings suggest that NFM has a reduced flood reduction impact in chalk groundwater-dominated catchments compared to non-groundwater dominated catchments. It is recommended that future research in this area focus on targeted application of NFM in sources of groundwater emergence, improved mapping of hydrogeological features, and manipulating soil properties via land management practices.

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Raw data and the R code script generated for and used for the analysis in Barnsley et al. (2021) can be found on Figshare. 10.6084/m9.figshare.14200229.

Research Thesis: Declaration of Authorship

Print name: Imogen Charlotte Barnsley

Title of thesis: Quantifying the Benefits of Natural Flood Management Methods in Groundwater-Dominated River Systems

I declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
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Signature: ....Date: 20/07/2022

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Definitions and Abbreviations

NFM .... Natural Flood Management. A paradigm of management strategies that aim to improve a catchment's resilience to prolonged and/or heavy rainfall by restoring, enhancing, or altering a catchment's natural hydrological and morphological characteristics.

SAC...................................... Special Areas of Conservation. An international designation that protects ecologically important sites for protection.

SSSI .... Site of Special Scientific Interest. A national designation for areas of land or water considered national heritage due to flora, fauna, geology, and geomorphology.

SEPA.................................... Scottish Environment Protection Agency.

RSuDs.................................. Rural Sustainable Urban Drainage Systems. Landscape features that intercept surface runoff and trap sediment before it leaves agricultural or arable fields

RAF...................................... Runoff Attenuation Features. A man-made landscape feature that intercepts and slows a hydrological flow pathway.

LWD .... Large Woody Debris. Large pieces of wood, usually entire trees, branches, or root plates which have fallen in to, or are placed within, a river channel.

BFI .... Base Flow Index. A measure of the percentage of stream flow that originates from sub-surface, slow-flow hydrological processes.

NRFA .... National River Flow Archive. A collection of full hydrological data for all of the gauging stations in the whole of the UK provided by the Centre for Ecology and Hydrology.

RBFI..................................... Richard-Baker Flashiness Index. Measures the sensitivity of a streamflow to rainfall inputs.

LCM..................................... Land Cover Map.

HOST ....Hydrology of Soil Types. Soil classes are grouped by hydrological properties, particularly their ability to transmit water bother vertically and horizontally.

RDA ....Redundancy Analysis. An asymmetric ordination method whereby the variation in one set of (explanatory) variables is used to directly explain the variation in another set of (response) variables.

VIF ....Variance Inflation Factor. A measure of the amount of multicollinearity in a set of multiple regression variables.

T&IRRS ....Test and Itchen River Restoration Strategy. A report written in 2013 outlining the river restoration policy recommendations for the River Test and Itchen catchments, Hampshire.

CES ....Conveyance Estimation System. A software tool developed in 2002 to improve estimation of flood and drainage water levels in river channels

PPB......................................Parts Per Billion. The number of units of mass of a contaminant per 1000 million units of mass.

SHETRAN ....Système Hydrologique Europeén-TRANsport. A three-dimensional coupled surface/subsurface difference model for coupled water flow, multi-fraction sediment transport and other reactive solutes transfer in river basins.

PET ....Potential Evapotranspiration. The sum of water evaporation and transpiration from a ground surface area to the atmosphere.

UKCP18 ....United Kingdom Climate Projections 2018.

RCP......................................Representative Concentration Pathways is a greenhouse gas concentration trajectory adopted by the Intergovernmental Panel on Climate Change.

IPCC.....................................The Intergovernmental Panel on Climate Change.

PELT ....Pruned Exact Linear Time (PELT) method.

CS ....Countryside Stewardship scheme. A government scheme where land managers agree to abide by a set of criteria that promote ecologically beneficial farming practices to qualify to receive a subsidy.

Ksat .... Saturated Hydraulic Conductivity refers to the rate at which saturated soils can transmit water.

Chapter 1 Introduction

1.1 Rationale

Flooding is one of the most pressing and prevalent risks in the UK. It has been estimated that approximately 5.2 million properties (equivalent to 1 in 6) in England are at risk of flooding (Environment Agency, 2009). This has implications in terms of high economic cost. In England, the 2015-2016 floods caused an estimated 1.6 billion in damages (Environment Agency, 2018). A small subset of these properties (between 122,000 and 290,000 or between 2.3% and 5.6%) are at risk from groundwater flooding due to being situated on chalk bedrock aquifers in the South East of England (McKenzie & Ward, 2015). The economic costs of groundwater and fluvial flooding are often combined (Fenn et al., 2016) making it difficult to calculate the direct cost of groundwater flooding. Whilst groundwater floods represent a small portion of England's overall flood risk, difficulties in predicting the location of flood waters originating as groundwater emergence mean that flooding of this origin represents a unique management problem and a significant local flood risk.

Climate change projections predict increased incidence in high intensity storm events making it likely that flood risk in the UK will increase in future (Brooks, 2013). There is also a general agreement that post-war land management practices and agricultural intensification led to degradation of river systems causing pollution, sedimentation, losses in biodiversity and, most importantly for this thesis, increased flood risk (Mainstone et al., 2008; Robinson & Sutherland, 2002; Skinner et al., 1997). This has paved the way to new land based and environmentally conscious methods for managing floods to be rapidly integrated into government policy (Penning-Rowsell et al., 2006) in recognition of the need to reverse historical damage exerted on the natural environment and the need for flood mitigation solutions that can be resilient to future climate change. Policies such as The Water Framework Directive (WFD, 2000, 60, EC), Defra's Water Strategy (DEFRA, 2008), the Making Space for Water initiative (DEFRA, 2004), and the Environment Act 2021 (Environment Act, 2021), as well as scientific reviews (Forbes et al., 2015; Pitt, 2008) all state a strong desire to manipulate land use for flood benefits. This is particularly prudent, given that climate change is projected to exacerbate seasonality in groundwater-dominated catchments, increasing the severity of drought in the summer and flooding in the winter (Lowe et al., 2019).

Natural Flood Management (NFM) represents a paradigm of management strategies that aim to improve a catchment's resilience to prolonged and/or heavy rainfall by restoring, enhancing or altering a catchment's natural hydrological and morphological characteristics (Forbes et al., 2015).

Strategies aim to increase interception and infiltration by reducing rapid runoff generation, increasing catchment water storage and slowing overland and river channel flows (Forbes et al., 2015; Quinn et al., 2013). NFM is a process-based intervention and functions by enhancing a catchments' natural ability to absorb 'shocks' from storms by intercepting sources of runoff and storing water in the catchment to then be slowly released (Barber & Quinn, 2012). NFM interventions can be categorised according to the processes that they manipulate (Dadson et al., 2017; Lane, 2017; Pitt, 2008): 1) the reduction of rapid runoff generation, 2) increasing catchment water storage, and 3) strategies to reduce the conveyance of water downstream. A successful NFM scheme reduces discharge at at-risk locations by extending a flood duration and reducing the peak discharge (and water level) at a point at any given time (Lane, 2017; Mclean et al., 2013).

Catchments underlain with chalk bedrock are mostly groundwater dominated (Sear et al., 1999) due to the highly porous chalk bedrock (up to 44%; Boving & Grathwohl, 2001), which allows large quantities of water to be stored and transmitted through the bedrock before being released into river channels. Groundwater flooding occurs when rainfall recharge causes the groundwater level to rise, in turn increasing groundwater inputs into river systems and groundwater emergence in topographic low points (Lamontagne et al., 2014; Naughton et al., 2018). NFM interventions seek to intercept runoff pathways and store surface water within the catchment to slow the flow of flood conveyance. However, a large proportion of the water in groundwater-dominated floods are transmitted throughout the catchment below the ground surface and emerge from bedrock sources, making it difficult to reconcile how NFM can be applied in these catchment types to intercept key flood flow pathways. Furthermore, rivers in chalk catchments have characteristically stable annual river regimes with relatively small variations between high and low flows and a lack of spate conditions due to slow transmission of water throughout the catchment within the bedrock (Berrie, 1992), a key property that NFM strategies aim to emulate by 'slowing the flow'. In fact, groundwater-dominated river systems are consistently raised as a gap in the NFM evidence base (Dadson et al., 2017; Lane, 2017; The Environment Agency, 2017) and in some cases are specifically mentioned as an exception to the presented evidence (Lane, 2017). Very little is known about how NFM might be implemented in groundwater catchments due to its limited implementation and difficulties in applying NFM to hydrogeological models that adequately represent these river systems. This thesis therefore focuses on addressing this gap in the evidence base.

1.2 Thesis aims

This thesis aims to establish whether NFM techniques can contribute to flood mitigation in groundwater-dominated chalk catchments. The specific research questions to be addressed are:

1. Are Natural Flood Management practices likely to reduce flooding in groundwater-dominated chalk streams? This research question is broken down into more specific tasks including:
    a. Mapping all gauged chalk catchments in England and developing a detailed database of their catchment properties and hydrological characteristics.
    b. Using this database, a detailed statistical analysis will be undertaken to understand:
        i. Which catchment properties define chalk catchment hydrology (and by extension the flood response). Understanding the nature of the flood response and their most influential catchment properties can be used to infer flood processes. This will be used to understand which chalk catchments have a greater compatibility with Natural Flood Management techniques. Chalk catchments will be categorised according to their compatibility with Natural Flood Management and mapped spatially.
        ii. Recommendations for applying Natural Flood Management in each chalk catchment category will be made. This is intended to help decision makers identify chalk catchments with the greatest suitability to Natural Flood Management implementation, and to choose measures which are most suitable for catchments under their responsibility.
2. What is the potential for flood reduction through the implementation of NFM in a chalk catchment?
    a. Methods for representing NFM in models will be assessed via a literature review.
    b. A fully distributed model is used to assess how modelled NFM implementation affects modelled flood peaks. Due to the complexity of representing chalk hydrogeological processes, this model is used as a generalised example of a chalk catchment and is based on data captured from the Rivers Test and Itchen which are generally considered as archetypal chalk streams. Data gathering will include:
        i. Compiling recorded hydrological data including rainfall, evapotranspiration, gauged discharge time series, water level times, and subsurface transmissivity for the study site.
        ii. Sourcing land use data.

iii. Field work will be used to obtain field-based manning's roughness values which are used to parametrise the river channel within the fully distributed model. Local knowledge and collaboration with the Environment Agency will be used to map Manning's roughness values across the river channel network of the Rivers Test and Itchen.

c. Flood metrics used will represent the dimensions of groundwater flooding. These include flood peaks, flood duration, the number of flood incidence and time of bank overtopping.

d. NFM scenarios will be compared to a non-NFM baseline scenario to understand the relative changes to flood metrics 'before' and 'after' NFM implementation in permeable chalk catchments.

e. NFM implementation will be assessed at multiple catchment sizes and with varied methods and scales of NFM intervention to understand how this affects flood peaks and flood duration.

3. How might future climate change alter the potential effectiveness of NFM implementation in groundwater dominated chalk catchments?

    a. A range of climate change scenarios from UKCP18 (RCP2.6 and RCP8.5) will be used to assess how NFM implementation stands up to the more extreme rainfall events in the future predicted by climate change models.

    b. All climate change scenarios are compared to a non-NFM climate scenario to understand the relative benefit of implementing NFM in permeable chalk catchments under future predicted extreme weather events.

This thesis is structured around the above research questions and hypotheses. Following a brief review of the relevant literature concerning rivers, flooding, NFM, and chalk catchments (**Chapter 2**), **Chapter 3** seeks to address Research Question 1 using redundancy analysis to link hydrological variability in chalk stream catchments to quantify the relationship between hydrological variability and key morphological characteristics that are amenable to NFM. These results are used to classify the catchments, infer flow pathways, and make suggestions for appropriate NFM strategies for these river basins. **Chapter 4** addresses Research Question 2 by generating a framework with which to parameterise a numerical model of a chalk catchment. This is achieved through targeted field data collection of reach-scale Mannning's *n* roughness coefficients established using the Aggregated Dead Zone model of dilution gauging. Field sites were chosen to represent a variety of chalk stream channel management practices to understand how the presence of vegetation and other channel features affect roughness in chalk streams. The information on roughness gained in Chapter 4 was used directly to parameterise the SHETRAN model to represent in-channel NFM interventions on the River Test in **Chapter 5.** Land use changes in the form of increased woodland area were also modelled. All scenarios are based on feasible changes in the Test catchment as all scenarios are based on the Test and Itchen River Restoration Strategy, a document published in 2013 outlining the threats to the chalk stream environment, and woodland opportunity mapping in the Test and Itchen catchments. The focus of chapter 5 is research question 3. Research Question 3 is addressed in **Chapter 6** by subjecting NFM scenarios from Chapter 5 to projected changes to rainfall according to UKCP18 projections. These model scenarios are used to assess the resilience to NFM practices in the chalk stream environment to future climate extremes. **Chapter 7** acknowledges that there is a requirement for further research in to applying Natural Flood Management in chalk catchments and explored the limitations of this research, as well as making recommendations for the direction of future research. This is followed by a summary of the key findings of this thesis and final concluding remarks in **Chapter 8**.

1.2.1 Chapter summaries

- **A literature review** outlining the current understanding and evidence base for natural flood management, an outline of the drivers and processes of groundwater flooding in chalk catchments and a short summary of cross disciplinary research into natural flood management methods in groundwater-dominated systems.
- **Exploring the capabilities of Natural Flood Management approaches in groundwater dominated chalk streams.** This chapter uses an asymmetric ordination method (redundancy analysis) to link hydrological variability in chalk stream catchments to quantify the relationships between hydrological variability and key morphological characteristics that are amenable to NFM for 198 catchments with chalk bedrock in the South East of England. These results are used to classify the catchments, infer flow pathways, and make suggestions for the most appropriate NFM strategies for these river basins.
- **Establishing the spatial extent of variable in-channel management and subsequent roughness values for hydraulic models on the River Test.** Manning's *n* roughness values were measured in the field on the rivers Test and Itchen using a dilution gauging method. Varied river channel management practices on these rivers leads to a spectrum of channel properties including channel bed and bank vegetation density, channel shape, and the presence or absence of large woody debris. This leads to a range of channel roughness values measured in the field. Field-measured values for chalk stream roughness are

supplemented with values measured in the literature to generate a set of Manning's *n* roughness values that can be used to parametrise numerical models.

- **Modelling the potential effect of NFM on flooding in the River Test catchment, England, using SHETRAN.** In this section the effect on flooding of in-channel NFM interventions (including river channel restoration, revegetation, and installation of large woody debris) and increasing woodland coverage for NFM are modelled in SHETRAN. SHETRAN is a physically based, fully distributed hydrological modelling system which can simulate the entire land phase of the hydrological cycle, including surface water and groundwater flows. This chapter includes a brief literature review of NFM modelling methods, a full account of model setup, scenario design and modelling results. The potential for in-channel river restoration and woodland creation as a flood mitigation strategy in chalk catchments is discussed. The Test catchment was chosen to represent an example permeable chalk catchments because it has been referred to as a 'typical' chalk stream.
- **The resilience of NFM interventions on the River Test to projected future climate change.** The effectiveness of NFM under projected future climate change scenarios is tested by comparing NFM flood mitigation scenarios to a non-NFM baseline. Future climate change scenarios are generated using the projected rainfall under UKCP18 climate change scenarios RCP2.6 (least warming due to an immediate significant cut in global emissions) and RCP8.5 (worst case – no attempt made to cut global emissions).
- **Limitations and future work.** The limitations of this suite of research are discussed and some suggestion of the areas of research regarding implementation of NFM in chalk catchments are made.
- **Conclusions**

Chapter 2 Literature review

2.1 Chalk streams: a unique river type

Chalk streams are internationally rare and are unlike any other river type in the world (O'Neill & Hughes, 2014). In England there are 224 rivers characterised as chalk streams which are a globally scarce combination of the hydrogeological characteristics present due to chalk bedrock and specific human interventions (O'Neill & Hughes, 2014). The unique properties of these rivers are due to the highly permeable chalk bedrock which underlie them. Because of this, large quantities of water in the catchment filters through the bedrock before emerging in springs and forming chalk streams which are characteristically mineral rich and very clear due to dissolved calcium and carbonate ions from the chalks and low quantities of suspended sediment. Chalk streams are lowland catchments, meaning they are low energy river systems (Mondon et al., 2021). All of this combines to generate a unique environment which supports a vast array of plant and animal life. The beauty and abundance of chalk streams attracts visitors from all over the world (O'Neill & Hughes, 2014). Due to their high biodiversity and the presence of rare or important species, four of England's chalk streams (the rivers Avon, Lambourne, Itchen and Wensum) are designated as international Special Areas of Conservation (SACs) and a further eight have sections of them which are nationally important areas of Special Scientific Interest (including sections of the rivers Test, Itchen, Bere, Frome, Nar, Kennet, Beut and Hull headwaters). England's chalk streams represent a unique habitat and hydraulic system. Traditionally they feature cool, very clear, and mineral rich water with gravel river beds which are capable of supporting a uniquely diverse ecosystem (O'Neill & Hughes, 2014). Stable flows and large quantities of nutrients provide optimal conditions for the growth of aquatic plants (maximum biomass recorded at 400g dry weight per meter square with typical levels around 200g dry weight per meter square) including Ranunculus (*Ranunculus penicillatus* and *Ranunculus calcareus)* which tend to dominate (Berrie, 1992). As well as aquatic vegetation, chalk streams support large populations of fish relative to other river types, especially brown trout, Atlantic Salmon and sea trout, making them famous hotspots for commercial fishing and angling (Berrie, 1992; Mann et al., 1989; The Environment Agency, 2013).

Chalk bedrock can be found globally and has existed in England for tens of millions of years (Hancock, 1975). However, the processes that formed England's unique chalk streams occurred at the end of the last Glacial Maxima. Approximately 10,000 years ago at the beginning of the Holocene, large quantities of glacial meltwater from the British and Irish Ice Sheet flooded across the

South of England, carrying with it glacial debris and gravel which now characterise many chalk stream channel beds (Berrie, 1992). Due to the large quantity of sediment carried by the glacial meltwater, these Holocene chalk rivers were braided and anastomose (Collins et al., 2006). Once the supply of glacial meltwater and glacial sedimentary material expired due to deglaciation, these chalk river systems became far more stable. Because they are lowland river systems, they have low transport capacity causing aggradation of sediment in smaller river channels which led to a slow migration to single-channel planforms over time (Collins et al., 2006).

Chalk streams are highly modified river systems, with human interventions dating back to Neolithic peoples who began altering chalk river processes via large-scale deforestation approximately 5000 years before present (Allen, 1992; French et al., 2005). Records demonstrate that the Romans were building bridges which led to changes in channel planform in the 1st century AD (Collins et al., 2006). The Anglo-Saxons during Medieval times harnessed the natural power of chalk streams via watermills which require additional side channels to operate them (Langdon, 2004; *The Doomsday Book*, 1086). Agricultural expansion in the 16th to 19th century led to the construction of water meadows which are man-made irrigation systems linked to the main river network, generating multiple extra channels and ditches (Cook et al., 2003). With centuries of modifications including the construction of sluices and multiple artificial channels for water meadows, mills and navigation, as well as channel realignment and/or deepening for land drainage (Brown et al 2018; Sear et al 199; Mainstone 1999), it can be said that the globally unique chalk stream environment is a product of the chalk geology, deglaciation processes in Southern England, and extensive human intervention over the course of millennia.

Post-World War II chalk stream management was characterised by anthropogenic forcing on the river system. The historical infrastructure, although largely unused for its original purposes, remained and was (and still is) an integral part of the hydraulic function of the river system whilst at the same time being valued for its cultural and historical importance (Brown et al., 2018). Notably, groundwater abstraction for civil water supply caused a drop in some local water levels resulting in enduring low flows (Wright & Berrie, 1987). Low flows and increased periods of dry river beds can modify the makeup of macrophyte, macroinvertebrate and fish communities, favouring species that can tolerate low flows or long periods of dry river beds (Westwood et al., 2017). Low flows can degrade ecosystems by depositing fine sediment on the channel bed which smothers macroinvertebrates and can restrict fish passage throughout the river system (Solomon & Paterson, 1980; Wood & Petts, 1999). The river channel began to be managed predominantly for commercial fishing leading to the now widespread practice of removing channel vegetation to aid the fish populations. Dredging was undertaken to reduce flood risk and the conversion of land use of the surrounding area from pastoral to agricultural land lead to increased pollution from fertilisers and a significant reduction in water quality (Bond, 2012) This has led to 75% of England's chalk streams to be designated 'heavily modified water bodies' in the 2008-2012 River Habitat Surveys and to be described as "in a shocking state of health" by the World Wildlife Fund UK and The Environment Agency (O'Neill & Hughes, 2014; The Environment Agency, 2013; The Environment Agency & English Nature, 2004). In response to this, there has been a concerted effort to manage chalk streams with a greater sensitivity to the ecosystem which supports the biodiversity, water quality, and flow maintenance, particularly since the turn of the millennium. In many cases this manifests as river restoration efforts which utilise strategies such as removal of unused historical infrastructure that retard flows and impede fish passage, the cessation of channel dredging, alterations to channel bank vegetation management regimes, restoring river channels to pre-altered planforms, the installation of large woody debris, and the reintroduction of gravel bed substrate and gravel cleaning (The Environment Agency, 2013). Other strategies are more legislative, such as the designation of areas such as the SACs and SSSI sites which are present on many chalk streams, and licensing agreements which limit abstraction rates to those which are ecologically acceptable (The Environment Agency, 2019). Results from predictive climate change models (such as the UK Climate Projection 2018 – UKCP2018) suggest that chalk stream characteristics and management will continue to evolve in the future. The UKCP2018 climate model estimates a 20-30% increase in winter rainfall and the same decrease in summer rainfall by the end of the century (Lowe et al., 2019). Under these projected conditions, there will be a marked increase in prolonged heavy winter rainfall, and in the summer a greater risk of overall drought conditions combined with increasingly severe convective rain storms (Lowe et al., 2019). Greater annual variation in flows will likely lead to increased flood risk during the winter and prolonged periods of low flows and droughts throughout the summer months putting pressure on public water supply. This will likely be highly problematic because the chalk aquifer accounts for 80% of public water supply in the South East of England (Lapworth & Gooddy, 2006). Furthermore, chalk streams have been shown to have a very limited ability to ecologically adapt to climate changes (Visser et al., 2019). As a result, climate change concerns in chalk streams are primarily associated with ecological degradation and increased dry and wet season variability (Herrera-Pantoja & Hiscock, 2007; Visser et al., 2019; Whitehead et al., 2006). These concerns will be required to be addressed immediately. It is therefore essential to accurately conceptualise the hydrological system of chalk catchments, as well as investigate the efficacy of environmentally conscious strategies such as NFM for managing future flood risk.

2.2 Groundwater-dominated river systems

Groundwater, in simplest terms, is a subsurface accumulation of water and is stored in the pore spaces of soil or rock and in rock crevices. Groundwater is an essential resource and provides base flow for many of the world's river systems, as well as being a valuable (and in some places essential) source for water abstraction. Groundwater is stored in porous bedrocks, which in the UK, are Permo-Triassic Sandstones, Limestone and Chalk (Sear et al., 1999). In England, a chalk outcrop area of 21,500 Km^2 (Figure 1) supplies 53% of the country's groundwater supply (Bradford, 2002). Chalk groundwater is the focus of this study because it represents the most acute risk of flooding relative to the other porous bedrock types (McKenzie & Ward, 2015). The reason Chalk is such an effective water store is due to the way in which it is formed. Most of Southern and South-Eastern England is dominated by chalk geology (Figure 1). Chalk is a soft sedimentary limestone rock formed during the Upper Cretaceous from the calcareous outer shells of planktonic algae, ranging in size from the original hollow shells called coccoliths to micron-sized plates of crushed coccoliths (Hancock, 1975). English chalk was formed about 90 million years ago over a period of approximately 35 million years. From 60 million years ago, uplift in Europe created a dome shape in the South East of England. Over time the soft chalk layer gradually eroded, forming chalk bands and escarpments found in the South, such as the South Downs. Tectonics in the Late Cretaceous, periglacial freeze-thaw cycles and weathering have led to fracturing of the Chalk bedrock mass (Royse et al., 2012). Because chalk is a limestone rock, these fractures can be widened over time by chemical karstification. According to Wheater et al. (2007), undeveloped chalk fractures range from a few microns to 1mm wide, but karstified fractures can be as wide as tens of centimetres. Pore spaces occur in the rock's sedimentary coccolith structure, as well as a fracture network, resulting in dual porosity which can be as high as 45% allowing large quantities of water to be stored in the bedrock (Wheater et al., 2007).

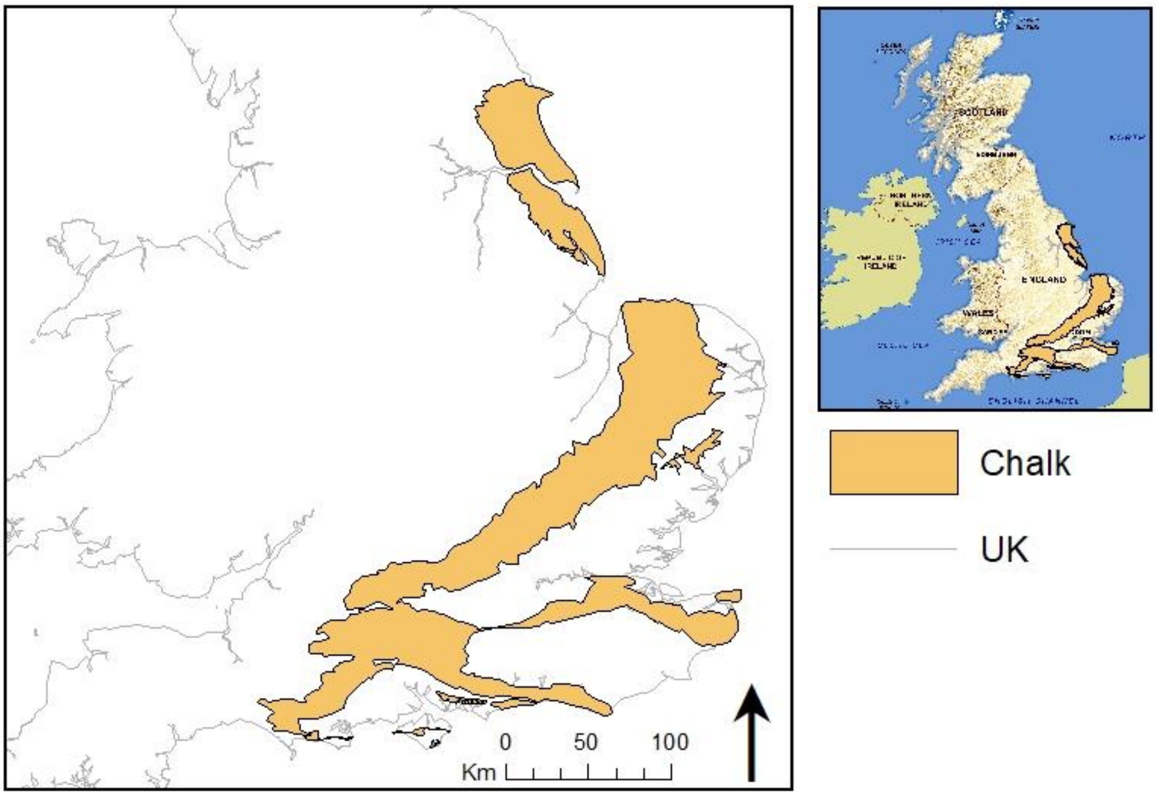


Figure 1 The location of exposed chalk bedrock in England.

The hydrogeology of Chalk is complex due to spatial variations in the conditions under which it was formed and weathering processes since. Preferential flow is caused by hydrogeological features such as bedding planes, hardgrounds and the fracture network (Michael Price, 1987; Wheater et al., 2007; Younger, 1989). Hardgrounds are areas of highly compressed, dense and impermeable Chalk, formed during tectonic activity and freeze-thaw cycles which can cause perched shallow aquifers and flow horizons (Arnott, 2008). Fractures in Chalk bedrock are relatively small for karstic features (approximately 10 – 1000mm in diameter) (Maurice et al., 2006). When fractures are saturated, water flows more freely through them than in the bedrock matrix due to reduced friction per unit area from the fracture walls due to increased hydraulic radius relative to the chalk matrix (Downing et al., 1993; Price, 1987). This allows water to be transferred in a catchment independent of the river network, coupling upland and down land hydrology (Molenat et al., 2008). Hydraulic coupling and groundwater emergence can be manifested as gaining or losing river reaches, where hydraulic gradients cause water to either flow in or out of the river channel from the bedrock, increasing or decreasing discharge independent of topography or flow accumulation downstream (Lamontagne et al., 2014). Groundwater emergence also occurs as features such as springs, ponds, and winterbournes. Because the location of hydrogeological features varies, so do preferential flow pathways. This means that water transfer throughout the catchment is not uniform across space and is dictated by the location, size, and activation of hydrogeological features. Activation of these features is largely due to variations in the groundwater balance.

The groundwater balance can be thought of as a simple bucket model: the sum of water inputs (recharge after rainfall - Stephens, 1996), and outputs (natural flows, springs, rivers and groundwater abstraction) (MaKenzie, 2010). Typically the groundwater balance is measured in terms of changes in the height of the water table which is the boundary between the saturated (pores filled entirely with water) and the non-saturated (pore spaces only partially filled) zones (Buddmeier, 2000). Where the water table height intersects with the ground surface, surface water occurs. Springs are winterbournes are two features characteristic of groundwater-dominated catchments. Springs occur as aquifer overflows at weak points in the bedrock. In cases where this forms a continuous flow of water, these often occur at the river source which form Chalk streams (Berrie, 1992). Alternatively, they can be intermittent and flow only when water tables and hydrostatic pressure are high (Atkinson & Smith, 1974). These intermittent springs are not always associated with the river network. Winterbournes are ephemeral streams found in the upper reaches and tributaries of Chalk streams and only flow when the water table is high (Furse, 1977). As the water table elevation migrates upwards, so does the source of the winterbourne due to dormant river channels in topographical low points.

Another characteristic feature of Chalk groundwater-dominated systems is the stable annual river regime, with relatively small variations between high flows and low flows, no sudden flooding or spate conditions (Berrie, 1992). Chalk stream hydrographs are long and smooth with relatively small and rounded peaks (Sear et al., 1999). This is due to the ‘buffer effect’ described by Berrie (1992) caused by the time it takes for water to infiltrate into the bedrock and travel into the river system. Because the Chalk is so porous, there is little surface runoff due to large bedrock storage capacity combined with high infiltration rates, allowing rainfall ‘shocks’ to absorbed. Because of this, it can take weeks or months for changes in rainfall to manifest as changes in the river regime (Wood et al., 2001). This causes lagged seasonal trends with high flows in spring and low flows in autumn. Groundwater river systems are also characterised by very clear and mineral rich water after filtration of solid particulates and solution of calcium carbonates during transmission in the bedrock (MaKenzie, 2010; Stubbington et al., 2017).

2.2.1 Chalk groundwater flooding

Because of the buffer effect, there is a strong seasonal oscillation in chalk groundwater heights in England, generally peaking in late spring with troughs in late autumn. Annual variation in rainfall patterns cause the exact time of year of groundwater peaks and troughs to shift. Groundwater stores are naturally very stable sources of water and account for the largest proportion of lower England's water supply (Parry et al., 2013). The chalk aquifer accounts for 80% of public water supply in the South East of England (Lapworth & Gooddy, 2006). Generally, larger fluctuations in water table heights are associated with human activity such as abstraction for domestic water supplies (MaKenzie, 2010), and major drought or flood events are often significantly improved or exacerbated by human interventions. When the water table height exceeds ground level, it results in groundwater-driven surface water flooding. Even within the UK, the characteristics and persistence of groundwater-driven floods vary spatially. Ascott et al. (2017) identified the main drivers of spatial variation in groundwater-dominated flooding as being: antecedent conditions, inputs and distribution of rainfall and local variations in the hydrological properties of both chalk and superficial deposits.

Antecedent conditions refer to the preparatory conditions that lead to flooding. In the case of groundwater-driven flooding it often refers to the rainfall and soil conditions in the lead up to the flooding event. The weeks prior to groundwater flooding are often characterised by prolonged rainfall and saturated soils. This is because prolonged wetness allows for gradual aquifer recharge. An example of this phenomena is the flooding event of 2012. March 2012 saw one of the most severe droughts in the UK for nearly a century causing soils to be uncharacteristically dry throughout winter and early spring. The drought ended abruptly in the wettest April - July in 205 years. Summer of 2012 saw groundwater-dominated flooding in July in Winterbourne Abbas in Dorset and normal surface water flooding occurred throughout the UK. Heavy and prolonged rainfall in late spring/early summer is uncharacteristic and meant that soils remained saturated throughout summer (Parry et al., 2013). Rain falling on dry winter soils aided in rapid aquifer recharge which reduced the time to reach saturation and full aquifer capacity, causing the water table to increase above surface level. Dry soils have reduced surface tension between soil particles allowing more drainage through the soil and into bedrock (Price, 1998). Drought over the winter creates antecedent conditions for rapid recharge. The subsequent prolonged rainfall caused the groundwater stores to recharge and the soils to become saturated which combined to cause conditions that brought one of the most widespread UK flooding events in recent decades.

Due to the nature of groundwater, the responses to rainfall such as high river discharge or flooding has a relatively long time lag relative to flood responses dictated by overland flow (Parry et al., 2013). Due to the severity of groundwater-driven flooding which occurred in 2012 and 2013/14 in Southern England, it became apparent that hydrological forecasting could be a useful tool for flood mitigation and planning strategies to be implemented during the lag time. As such, a three step method is used where rainfall forecasts are used to predict future groundwater levels based on past rainfall and the concurrent rainfall patterns (Prudhomme et al., 2017). This is a first attempt at this sort of hydrological forecasting, but model results show a high level of accuracy, particularly in the permeable groundwater catchments of Southeast England. That historic rainfall patterns and future rain forecasts can be used to make reliable predictions of groundwater flooding demonstrates that rainfall is a key a predicting factor as to the type and severity of groundwater flooding. Spatial variation in flooding can be explained by the variations in rainfall patterns because rainfall patterns and floods vary over space at a catchment and sub-catchment scale, but droughts do not (Ascott et al., 2017). Future predictions of increased magnitude and frequency rainfall events under climate change have the potential to increase groundwater-driven flooding incidence by up to four times (Ascott et al., 2017).

Characteristic variation in chalk bedrock and superficial materials occur because of variation in historical conditions that formed hydrogeological features and deposited superficial material. For example, in the UK, the band of cretaceous chalk that extends from Hampshire up to Norfolk (including the Thames headwaters) has variable characteristics when moving from North to South. This is because the north and North-East section of chalk (in Norfolk) was glaciated during the last glacial maxima. Therefore, the chalk was exposed to extreme pressure and as such has many small stress fractures within it. Superficial deposits are made up of fine-grained glacial till, clay and flints which are impermeable. This significantly lowers the rate of infiltration and slows the rise to recharge and recession under (seasonal) changes in climate (Ascott et al., 2017). This makes the groundwater system in this region comparatively less responsive to climate forcing, making it a more stable aquifer. However, if/when floods in this region do occur, impermeable superficial deposits mean that there is a greater quantity of runoff generated, causing a more flashy hydrological response in the chalk catchments of the North East than in the South where superficial deposits are permeable.

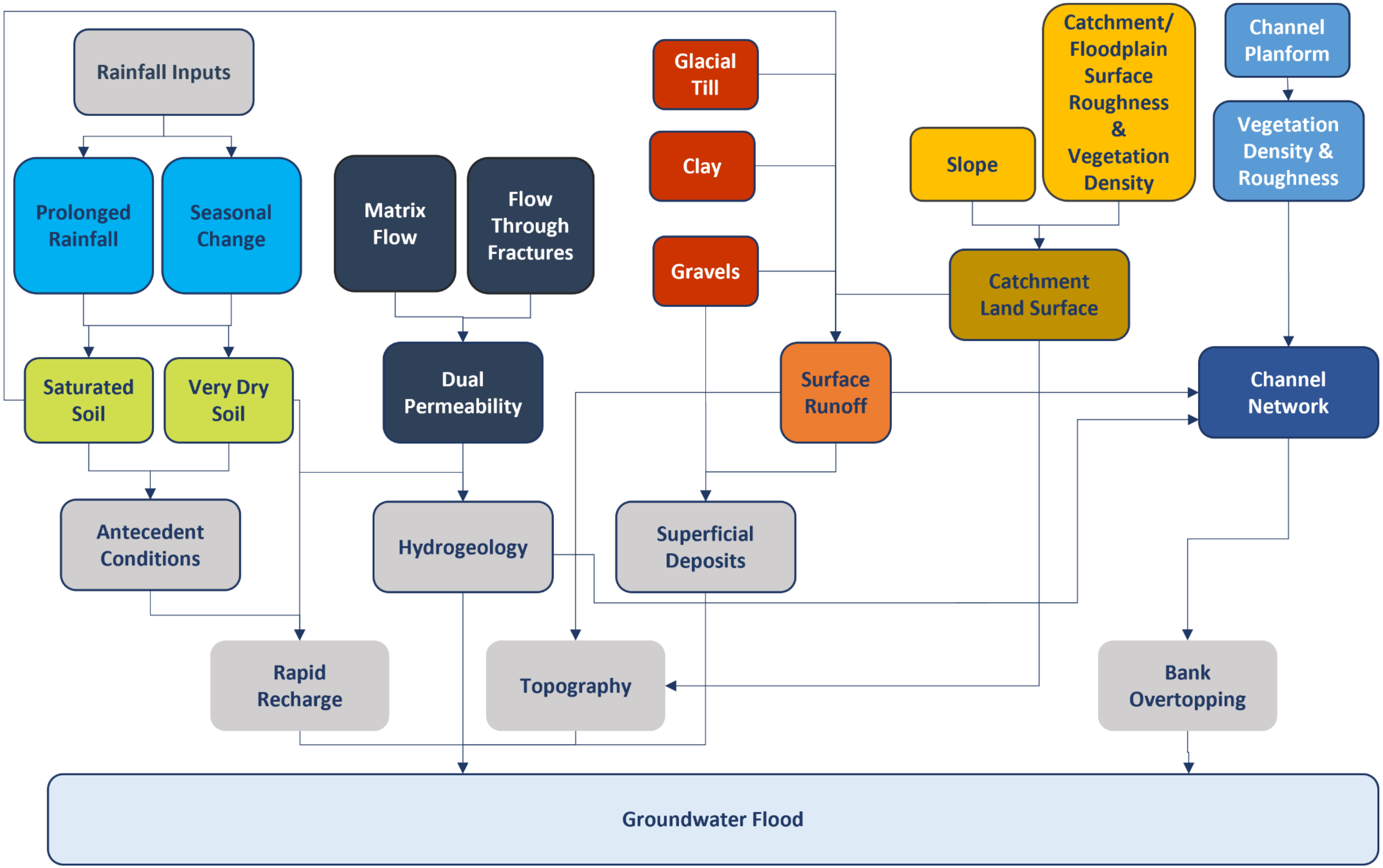


Figure 2 A conceptual model outlining the hydrological system and physical catchment porperties which contribute to groundwater flooding. Arrows indicate the relationship between factors, with antecedent conditions, hydrogeology, superficial deposits, being the main factors that contribute to rapid aquifer recharge and bank overtopping in a groundwater flood.

The south of the chalk band (Wessex and the South Downs) experienced periglacial conditions during the last glacial maxima and was exposed to the systematic freezing and thawing that is characteristic of these landscapes. This has led to some interesting characteristics that increase the complexity of bedrock in these regions. One example is the occurrence of hardgrounds. As the water in the pores of the calk expanded and contracted throughout freeze-thaw cycles, the structure of the bedrock was destroyed, leaving regions of low permeability (5%) compacted chalk dust. Hardgrounds are continuous throughout the chalk and can be important groundwater flow horizons, often making them useful marker horizons (Wheater et al., 2007). The superficial deposits in this region are also very different to those in the northern region and are generally permeable fluvial gravels deposited by the ancient Solent River (Allen & Gibbard, 1993). The difference in superficial deposits makes this one of the most responsive groundwater-dominated regions in the UK, with the water table fluctuation more frequently due to quick recharge and recession and faster groundwater responses to rainfall (Ascott et al., 2017).

As well as variations in the rate of aquifer recharge, the permeability of superficial deposits also dictates surface runoff generation. More permeable superficial deposits allow greater recharge rates and more surface runoff generation and vice versa for impermeable superficial deposits. As a result, chalk catchments in the Northeast of England have a greater proportion of surface runoff processes than chalk catchments in Southern England. Surface runoff is conveyed through the catchment via overland flow processes, which describes surface flows outside the confines of the river channel (Kampf & Mirus, 2013), until eventually flowing in to the river network. As water flows over the land surface, it encounters resistance due to microfeatures such as variations in microtopography and vegetation which affect the direction and rate of flow in overland pathways (Bergkamp, 1998). This resistance from these features can be summarised as surface roughness. The rate of overland flow is also affected by the shape (plan and profile) of the hillslope or catchment surface. The hillslope shape dictates the gradient and therefore the depth and velocity of overland flows (Kampf & Mirus, 2013).

Eventually, all overland flows contribute to in-channel flows which transfer downslope through the channel network until eventually reaching the ocean. River channels receive water from overland flow sources, as well as baseflow which is originates from the aquifer via hydrogeological pathways. Chalk rivers are highly groundwater dominated and as a result, constant fluctuations of river discharge in response to fluctuations in the water table height are also characteristic of groundwater streams. The rate and responsiveness to changes in groundwater levels are dictated by the connectivity of rivers to the groundwater supply in the riparian zone (Lamontagne et al. 2014).

Generally rivers become more connected to groundwater sources of water when the water table is elevated (Aubert et al., 2013) and conversely become decoupled when the water table is low leading to fluctuations in river discharge. The rate at which river reaches gain or lose water depend on many factors. One of these is the pressure gradient. In a connected reach of river, a pressure gradient is created by the flow of the groundwater through the matrix and the pressure exerted on the channel walls in the river. Where the pressure of groundwater is higher than that of the opposing pressure of water in the rivers, it is a gaining reach, and vice versa. The balance of these pressure gradients vary and have been shown to vary over the course of a rainfall event (Voltz et al., 2013). However, this is dependent on the hydrological properties of the bedrock. Generally, there is a time lag between a hydrological response (changes to WTH and pressure gradients) as rainfall percolates in to the bedrock which can take days or weeks (Parry et al., 2013). Factors such as steep slopes surrounding rivers are also more likely to maintain a high-pressure gaining reach. Streambed properties also affects the connectivity of river reaches to the aquifer with more porous streambeds allow rapid transfer of water throughout the riparian zones. The coarse gravel streambed materials that are characteristic of English chalk streams are optimum for riparian groundwater exchange (Dor et al., 2011). Dor et al. (2011) also noted that hydrogeological effects are also important. Where water table contours are parallel with a river reach, it will be a strongly gaining reach (Finch et al., 2004). Therefore, aquifer size, shape and orientation are also important in dictating the rate of transfer of water in or out of the river channel from bedrock sources.

The river network is important because it provides the predominant pathway by which surface water is transported through the catchment. River channel pathways directly control the relationship between discharge and water levels by local channel properties which affect the speed and attenuation of a flood wave as it passes through the drainage network (Lane & Thorne, 2007). The hydraulic roughness of the river channel describes the flow resistance caused by the friction of water flowing through the channel network. Hydraulic roughness is generated by river network features such as channel bed material, the irregularity of the channel and bank material, the spatial variation of cross section size and width, physical obstructions within the channel, bed and bank vegetation, and the sinuosity of river channels (Cowan, 1956). The channel capacity is determined by the width and depth of the channel and the density of bed and bank vegetation. The chalk stream environment provides optimum conditions for aquatic vegetation growth and therefore naturally have large quantities of trailing bed and bank vegetation which can reduce the channel capacity seasonally, raising water levels and increasing flood risk (Berrie, 1992; Sutcliffe, 2014). Channel conveyance is a quantitative measure of the discharge capacity of watercourse and describes the ability of a river channel to transmit water downslope and is dictated by a combination of the spatial variation in channel hydraulic roughness, channel capacity and discharge. As a result, bank overtopping events which occur in groundwater-dominated chalk catchments are a function of groundwater baseflow inputs, overland flow inputs, channel planform and the spatial variation of features that help or hinder channel conveyance. Figure 2 is a conceptual model that demonstrates all the factors and features that are involved in generating groundwater flooding in areas underlain by chalk bedrock in the UK.

2.3 Natural flood management

Natural Flood Management (NFM) is defined in the Scottish Environment Protection Agency (SEPA) Natural Flood Management Handbook (Forbes et al., 2015, pg. 6) as "involve[ing] techniques that aim to work with natural hydrological and morphological processes, features and characteristics to manage the sources and pathways of flood waters. These techniques include the restoration, enhancement and alteration of natural features and characteristics, but exclude traditional flood defence engineering that works against or disrupts these natural processes". NFM works on the premise that post-war degradation of river systems has increased flood risk, and by modifying catchments to a more natural hydrological function, flood risk will be reduced (Pitt, 2008). As stated in the SEPA definition which has been widely adopted, traditional 'hard' engineering interventions are not included in NFM because they are not flexible enough to deal with a multitude of different flood conditions and future climate change, cause harsh step changes in river regime, are expensive to install and require constant maintenance.

In his extensive literature review of NFM techniques, Lane (2017) put them into three categories.

1) NFM strategies aim to reduce rapid runoff generation by changing agricultural land use practices, changing field drainage structures, employing the use of buffer strips and buffer zones and afforestation
2) NFM strategies aim to store water in ponds, bunds, ditches, wetlands and by impounding flow
3) NFM strategies aim to reduce the conveyance of water downstream by reducing hillslope-channel coupling, management of the riparian zone and within channel realignment).

He summarises NFM, therefore, as the management of runoff and channel flow attenuation to reduce discharge at at-risk points in the catchment. This is an important addition to the NFM definition because the success of an NFM scheme is often measured using the resultant hydrograph at these key risk points. A successful NFM scheme will reduce discharge at at-risk locations by 'flattening the curve' by lengthening and reducing a flood peak, reducing the peak discharge at a single point at any given time (Lane, 2017; Mclean et al., 2013). The idea is to enhance the catchments natural ability to absorb ‘shocks’ from storms by storing water in the catchment and then slowly releasing it (Barber & Quinn, 2012). This is achieved by increasing interception and infiltration, slowing overland channel flows and manipulating channel and catchment surface roughness (Quinn et al., 2013; SEPA, 2012). As mentioned in the SEPA definition, NFM is a process-based approach which means that schemes are most effective when they are designed specifically to manipulate the dominant processes within that catchment. Categories 1 and 2 of NFM techniques as outlined by Lane (2017) focus on intercepting and modifying surface runoff pathways to ‘slow the flow’ to river channels. The most common NFM interventions are outlined in Table 1 and are sorted according to the processes they impact as outlined by Lane (2017).

2.3.1 Reducing runoff generation for NFM

NFM measures which are used to reduce runoff generation are generally associated with altering land use and land management practices. Converting other land use types into woodland can be a highly effective management strategy to reduce surface runoff generation. As shown in Figure 3, trees have a relatively complex hydrological interaction. Leaves and branches cause a physical obstruction to precipitation hitting the ground surface, a process called interception. Depending on the leaf area and size, small quantities of water are stored directly on the leaves where they are evaporated due to heat from the sun and wind. Trees also absorb water from the soil through root uptake. This therefore increases the capacity of the soil to store water within it as water is removed by trees. Additionally, trees store a large quantity of water within them which is used for biological processes. Evapotranspiration is the process of trees excreting water from their leaves as a biproduct of photosynthesis. The root network of a tree also generate preferential flow pathways for water via infiltration, meaning that net rainfall (the total amount of rainfall which reaches ground surface after interception and evaporation) water can percolate more deeply beneath the ground, occasionally increasing infiltration rates beneath mature trees (Rosenqvist, 2007). The runoff reduction potential of tree planting is well understood. Huang et al. (2003) demonstrated using paired catchments that runoff reductions of up to 32% could be generated by planting trees in 80% of a river catchment over 30 years. A strong trend demonstrated that annual runoff reduction increases with the age of the trees and runoff rates were seasonal, with trees storing the most water between June and September. Runoff reduction also translated to reductions in peak flows during storms. These findings are reflected in other studies (Dadson et al., 2017; Iacob et al., 2017; Robinson, 1986; Rosenqvist, 2007).

Table 1 Examples of the most common NFM treatments and how they were classified according to the processes they utilise to reduce flood flows according to Lane (2017).

Class of NFM according to Lane (2017)	Type	NFM treatments	Example
Runoff reduction	Afforestation		(Huang et al., 2003)
	Changes in arable land use practices	Winter cover crops	(O'Connell et al., 2007)
		Changing tillage practices	(O'Connell et al., 2007)
		No till farming	(O'Connell et al., 2007)
	Reduction of livestock density		(O'Connell et al., 2007)
	Field drainage	Rural Sustainable Drainage Systems (SuDS)	(Callow & Smettem, 2009)
	Buffer zones and strips	Plants across the slope – hedgerows, tree belts and buffer strips	(Dadson et al., 2017)
Within-catchment water storage	storage ponds	Online storage ponds	
		Offline storage ponds	
	Wetlands	Wetlands	(Bullock & Acreman, 2003)
	Wash lands	Controlled flooding of selected low-risk areas of flood plain	(Charlesworth & Booth, 2016; S. N. Lane, 2017a)
	Impounded storage	Regulated release of dam water	(Maheshwari et al., 1995)
Reduced flow attenuation	River restoration	Channel realignment – increase sinuosity	(M. C. Acreman et al., 2003a)
		Large Woody Debris and leaky dams	(Adams et al., 2019)
		Re-vegetating margins	
	Management of riparian conveyance	Increased riparian vegetation	(Anderson et al., 2006)

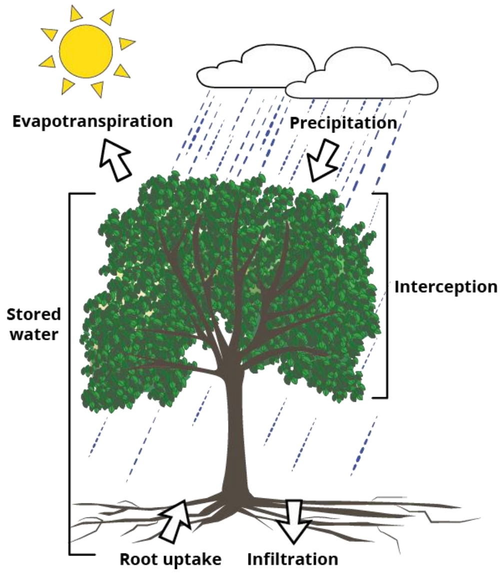


Figure 3 The processes of evapotranspiration and water storage in trees. From Mississippi Watershed Management Organisation (2017).

Land management practices can also be used to reduce runoff reduction by manipulating soil water properties. It is generally agreed that agricultural intensification in the UK during the 1950s, and the land management practices that accompanied it, have led to increased runoff generation in rural areas. Practices that increase surface runoff generation are increased stocking densities (leading to soil compaction), autumn sowing and late harvesting (Holman et al., 2003), the removal of hedgerows (Wheater & Evans, 2009), underground drainage (Robinson et al., 1985), driving machinery over wet soils (Young and Voorhees, 1982), and drainage ditches (Robinson et al., 1985). Conversely, surface runoff generation can be reduced using land management practices such as no or low tillage methods (Jat et al., 2009), winter cover crops (Schafer, 1986) and vegetated buffer strips and hedgerows (Ghadiri et al., 2001). Reducing stocking densities, changing tillage practices and using cover crops are all effective at reducing runoff generation by increasing soil organic content and reducing soil bulk density in the top 10cm of soil (Çerçioğlu et al., 2019). This is directly related to the pore sizes in the soil, with reduced bulk densities and increased organic soil content related with larger pore spaces and a greater ability for the soil to hold water (Skaalsveen et al., 2019).

Buffer strips, tree belts and hedgerows are typically found at boundaries of farmland and grasslands as well as near water courses and are formed of long strips of natural vegetation such as trees and bushes. These features are often strategically placed perpendicular to the landscape slope and therefore the direction of runoff (Figure 4). They operate by forming a natural barrier to flows by increasing surface roughness and generating partial storage due to their water infiltration and evapotranspiration capacity. It is theorised that buffer strips, tree belts and hedgerows attenuate surface water energy, reducing soil erosion and sediment transport from field runoff (The European Commission, 2014). Sediment trapping and conveyance reduction potential are related to the thickness of the vegetation belt, with thicker belts slowing the flow more (Borin et al., 2005). Whilst hedgerows and buffer strips have been shown to be capable of reducing flood flows in modelling studies (Strosser et al., 2014), the greatest benefits associated with these measures are their ability to trap sediment runoff from arable land and the associated nitrates and phosphate which can cause damage to riverine ecosystems (Borin et al., 2005).

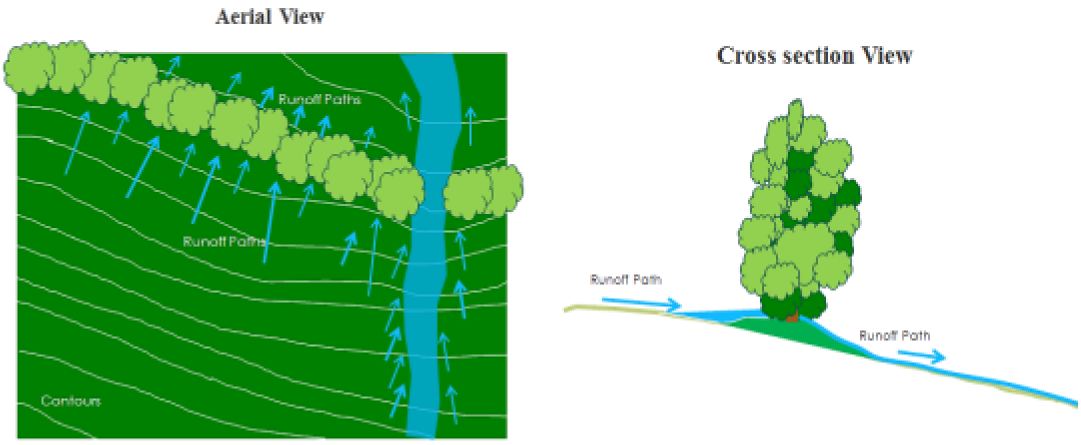


Figure 4 A figure from Samra (2017) demonstrating the process of flow interception and thereby flood reduction from buffer strips, tree shelter belts, and hedgerows from.

The same can be said for Rural Sustainable Urban Drainage Systems (RsuDS) or Runoff Attenuation Features RAFs). These are usually an ensemble or individual features placed within a catchment which are designed to intercept, divert, and capture water and sediment before it reaches the river channel from farmed fields (Figure 5). These generally take the form of ditches, drainage blocking to trap sediment, raised areas of land called bunds and sequential pools for trapping sediment. Studies show that features such as these are highly effective at trapping sediment and reducing the quantities of nitrates and phosphates that enter the river channel via landscape-channel coupling (Callow & Smettem, 2009). Whilst their primary function is capturing pollutants, this process requires capturing and storing a large quantity of runoff temporarily within the catchment (up to $8000m^3$ – (Adams et al., 2018)) which has been shown to slightly delay flood peaks but has little effect on peak magnitude (Callow & Smettem, 2009).

Figure 5 A sequential series of pools designed for water capture and sediment trapping for runoff from arable land from Adams et al. (2018).

2.3.2 Increasing catchment storage for NFM

Storage ponds are designed to create additional water retention within the catchment, slowing the rate at which water enters the river channel or attenuates downstream. There are two types of storage ponds, online and offline. Online storage ponds (Figure 6.a) are connected to the river channel and are often used as overflow areas used to store excess river flows, storing the water temporarily and then releasing it slowly back into the river channel. This can be used to attenuate flows and mitigate against excessing bank overtopping by siphoning off the top water levels. Offline storage ponds (Figure 6.b) are designed to intercept surface runoff pathways and collect runoff from the catchment area and store it within the catchment. Both online and offline storage ponds can be built by lowering the ground surface by digging a pond area, or by building up earth or materials to capture water. Both are designed to release water gradually and can feature spillways to control the direction of flow when the storage is exceeded to limit damage and flooding to the area surrounding them.

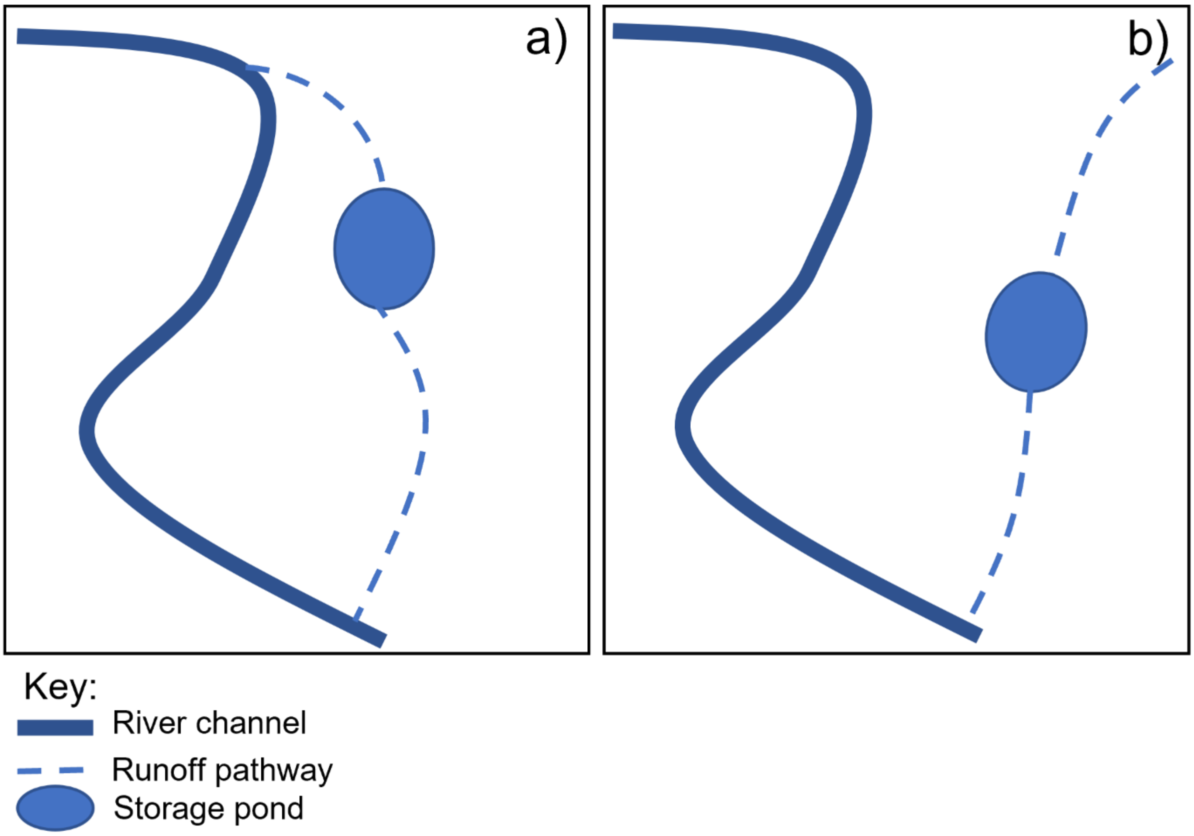


Figure 6 Schematic demonstrating the difference in flow pathways intercepted by online (a) and offline (b) flood storage ponds.

The physical premise behind storage ponds for NFM is relatively simple: by increasing the volume of water a catchment can store before it reaches capacity, rainfall and runoff can be intercepted and stored within the catchment, lowering channel conveyance, flood peaks and bank overtopping (Nicholson et al., 2020). Research by Lockwood et al. (2020) in the South of England shows that increased storage after from offline storage ponds led to peak flow lags at a downstream gauge compared to an upstream gauge. Longer recession limbs downstream of storage pond were also recorded, demonstrating the buffering effect of capturing, storing and slowly releasing runoff in additional catchment storage (Lockwood et al., 2020). Storage ponds (or storage areas) have also been shown to be a useful method to mitigate the replacement of permeable surfaces with impermeable surfaces during urban development by attenuating runoff and replicating the previous slower runoff processes (Hall et al., 1993). Within the literature, storage ponds have generally been shown to be a highly effective strategy for reducing flood peaks (Hall et al., 1993; Hewett et al., 2020; Nicholson et al., 2012; Yazdi & Khazaei, 2019), with flood peak reductions of up to 30% immediately downstream (Nicholson et al., 2020).

Wetlands are areas of saturated land and include multiple different land types, including wet woodland, reedbeds, peat bogs, fens, and salt marshes (Acreman & Holdon, 2013). Wetlands reduce flooding under the same physical processes – by functioning as a large storage area for water within the catchment and acting as an intermediary zone between surface runoff and the river channel (Watson et al., 2016). A systematic review suggests that floodplain wetlands are the most effective at generating flood reductions and typify the flood benefits often associated with wetlands, including flood peak reductions, groundwater recharge, and augmented low flows (Bullock & Acreman, 2003). Wetlands are highly prized ecosystems partly for their flood mitigating properties, but predominantly because they are ecologically valuable. Wetlands improve water quality by filtering water through the soils, they provide critically important habitats for a wide variety of plant and animal species (many of which are endangered), have been shown to be able to regulate micro and macro climate changes, and have been shown to be culturally and economically important by providing highly fertile and productive land (Brandolin et al., 2013; Bullock & Acreman, 2003; Gumiero et al., 2013; Ming et al., 2007).

2.3.3 Reducing downstream conveyance for NFM

Among one of the most common NFM strategies employed (due to the relative ease of implementation) is the use of Large Woody Debris Dams (LWDs) or leaky barriers. Large woody debris dams describe pieces of dead wood thicker than 1cm in diameter and longer than 1m which accumulate within the river channel, interlacing to form a natural barrier (Linstead & Gurnell, 1999). They can form naturally because of deadwood falling naturally in the river channel or can be formed artificially by purposefully placing deadwood it in the channel to form a blockage. Leaky barriers, or 'engineered' LWD are usually constructed of wood and are fixed in place across the river channel in a manner than obstructs but does not fully impede river channel flow. The hydrological effect of both LWDs and leaky barriers are the same – the river channel flow is retarded leading to slower flows and raised water levels in the vicinity immediately upstream of the woody debris.

LWD and leaky barriers range from large channel-spanning leaky barriers which can store large quantities of water, down to the more naturally occurring LWDs which tend to occur in wooded floodplain in catchment headwaters (Dixon & Sear, 2014; Wohl, 2013). By partially blocking the river channel, LWD cause complex hydraulic variations, generating non-uniform areas of aggradation and scour as flows interact with natural roughness elements (Faustini & Jones, 2003; Wenzel et al., 2014) A series or network of LWD can generate a stepping formation, interrupting local channel slope and

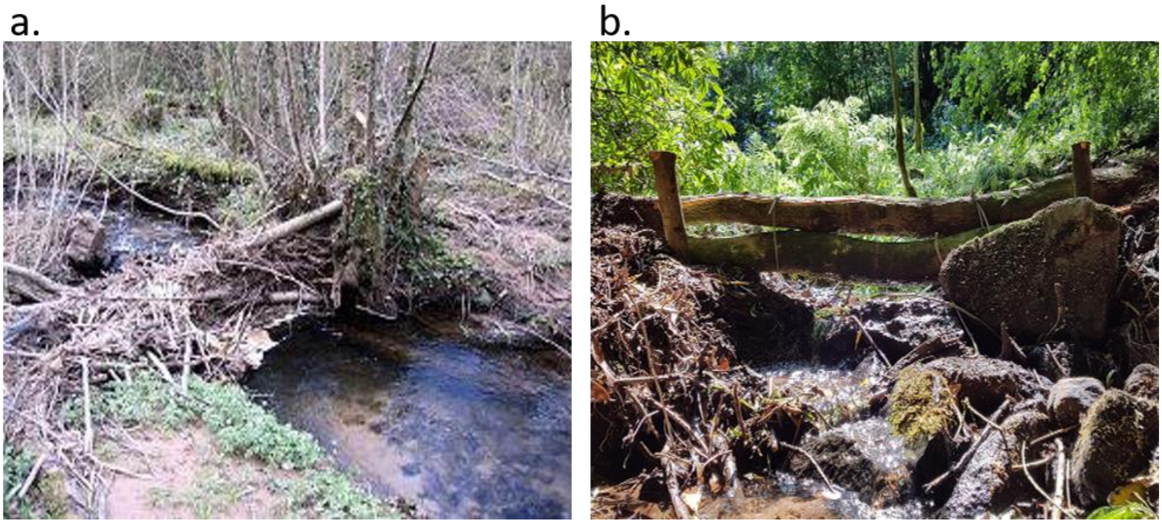


Figure 7 Examples of Large Woody Debris dams implemented as part of Natural Flood Management Schemes.

moderating average channel slope over a large area (Faustini & Jones, 2003). Stepping caused by LWD and the significant drop in velocity and head upstream of LWDs has been compared to flow over a weir, particularly in high flows (Muhawenimana et al., 2021). Because of the drop in head upstream of LWDs, they can cause significant sedimentation which is often viewed as an additional benefit due to potential improvements in water quality downstream (Wohl, 2013).

Reduced channel cross-sectional area from the barrier obstruction and sedimentation and increased flow resistance can force water out of the river channel and on to the flood plain, further increasing the storage potential and attenuation effect of woody debris and channel obstructions (Faustini & Jones, 2003; Wohl, 2013). Water pooled on the flood plain for longer periods of time can also increase ground infiltration, increasing water storage within the catchment and further attenuation surface flows (Quinn et al., 2013; H. Thomas & Nisbet, 2012). This process of increasing channel hydraulic roughness by obstructing flows and forcing water on the channel flood plain can provide flood alleviation by delaying the flood peak and increasing flood travel time (Faustini & Jones, 2003; Gregory et al., 1985; The Environment Agency, 2017; Wenzel et al., 2014).

River restoration schemes, which is some cases are completed as part of NFM schemes, have also been shown to have flood reduction benefits. This, again, is often due to allowing channel-floodplain reconnection. Acreman et al. (2003) found that by restoring channel geometry to pre-engineered conditions (re-meandering the channel planform and removing channel embankments) significant quantities of water were able to spill on to the floodplain, reducing peak flows downstream by up to 15%.

Riparian vegetation, vegetation, and riparian woodland can reduce channel conveyance by increasing hydraulic roughness directly adjacent to the river channel which can slow the rate at which water is delivered to the channel capturing sediment. Additionally, in higher flows, a riparian zone with dense vegetation, high roughness, and flow resistance can introduce shear stress reducing conveyance (Kean & Smith, 2004). Increased roughness and reduced velocities increase sediment deposition on the floodplain. Riparian planting and the presence of mature trees in the riparian zone has highly localised evapotranspiration effects, with tree roots drawing water up from the soil, diverting it from baseflows, and storing it within the trees or to the atmosphere as evapotranspiration (Tabacchi et al., 2000). There is a lack of long term data on the effectiveness of riparian planting due to the time it takes for trees to mature so the majority of benefits from these measures are gained from hydraulic models which focus on the roughness effects of riparian woodland (Anderson et al., 2006). Additionally, riparian vegetation makes the formation of LWD more likely, meaning the effects of LWDs can, and often are, combined with the effects of riparian vegetation (Nisbet et al., 2015).

2.3.4 The current evidence base for NFM

The evidence base suggests that the relative impacts of NFM measures are highly scale dependent (Pitt, 2008). There is strong evidence to show that local scale NFM measures produce highly effective local scale effects. For example, Quinn et al. (2013) were able to use a network of ponds to store up to 30% of the flood peak, Jackson et al. (2008) found that strategically placed tree shelter belts can reduce peak flows up to 40% and Acreman et al. (2003) found that river restoration can reduce the flood peak by 15%. However, there is no substantial evidence to show that multiple small scale measures upstream aggregate to cause any significant impact downstream (O'connell et al., 2007). Additionally, Lane (2017) found that increasing the percentage of the catchment impacted by NFM measures doesn’t cause a linear increase in attenuation, summarising that more is not always better. In fact, dramatic as they are, an extensive review demonstrated that impacts this great are only seen in catchments <20Km^2 (Dadson et al., 2017). Lane (2017) also found that distance from NFM implementation also caused a reduction in measured attenuation benefits, meaning that the scale and location of the attenuation effect is important to consider when implementing NFM. Therefore, NFM is most effective in smaller headwater catchments. Additionally, NFM has been shown to have the most impact in smaller scale flooding events. Parrott et al. (2009) found that NFM produced no flood benefits for a 1:100 or 1:200-year return period event. This finding holds true for all catchment types (Salazar et al., 2012). Therefore, NFM works best on smaller catchments for lower return period floods.

Another application of NFM methods is to desynchronise flood waves from different tributaries, reducing the overall flood peak downstream or at a high-risk point (Metcalfe et al., 2017). This would be achieved by implementing NFM in one sub-catchment, allowing NFM to have a high impact in that region. By delaying one flood wave in one sub-catchment and allowing the other sub-catchment to function as normal, it decreases the likelihood that these two flood waves will synchronise. As long as subsequent flood waves do not resynchronise downstream, these methods can be highly effective (Dixon et al., 2016). Importantly, the effect of desynchronising sub-catchment flood waves works theoretically at every scale (Pattison et al., 2014). Metcalfe et al. (2017) indicates that large portions of the benefits of NFM come from its ability to desynchronise sub-catchment flood waves and that any measures that do not achieve this effect do not realise the full potential of NFM.

Very few large scale NFM schemes have been implemented and the studies that come from them are inconclusive (Murgatroyd & Dadson, 2019; O'Connell et al., 2007). Monitoring NFM schemes and isolating the attenuation effects of singular and multiple NFM features was highlighted as one of the main gaps in the NFM literature in the review by Dadson et al. (2017). As it stands there isn't enough evidence to make causal links between NFM and flood reduction downstream (Dadson et al., 2017). There may be many reasons for this, but the consensus is that it takes a lot of time to implement NFM and observe the effects. Particularly for interventions such as afforestation, vegetation or river restoration where it takes time for the implemented intervention to mature. Scientific study of NFM is still in its relative infancy, making the evidence base for conclusive findings at the catchment scale relatively sparse (Cooper et al., 2021; Lane, 2017; Wingfield et al., 2019).

2.3.5 Barriers and benefits to the uptake of NFM

The main advantage of NFM over other flood interventions are the multiple benefits. Where NFM has been implemented, the added ecological advantages that come along with these kinds of measures are a major factors for decision makers in choosing NFM over other possible interventions (Bark et al., 2021). Furthermore, local communities tend to favour NFM schemes over 'hard' engineering schemes for aesthetic reasons. NFM interventions such as ponds, bunds, wetlands, leaky barriers and large woody debris can be easily engineered to blend in to the local landscape and can even be used as an opportunity to improve green and blue spaces making them a hugely attractive proposition to the public compared to potentially 'ugly' engineered flood defences (D'Souza et al., 2021; Short et al., 2018).

Additionally, there are abundant potential ecological benefits associated with NFM. One of the main aims of NFM is 'slowing the flow'. As a result, interventions such as vegetative buffer strips, storage ponds and woody debris in the river channel can generate drops in velocity, trapping and storing sediment in or behind these features (Piégay & Gurnell, 1997; Wohl, 2013). Particularly in cases where agricultural sediment is impregnated with harmful pollutants such as phosphates and nitrates, the sediment trapping effect of physical barriers and water stores for NFM have been shown to improve water quality in the river network (Forbes et al., 2015). Physical obstructions like in-channel large woody debris generate multiple hydrological conditions and flow rates which can house a greater variety of macroinvertebrates and increased taxa richness (Deane et al., 2021). These benefits extend beyond the locality of the large woody debris and benefit the whole river channel. Land management methods that are included in NFM, such as cover cropping, reduced tillage and reduced livestock density can also reduce the mobilisation of agricultural sediment in the first place by binding soils together and maintaining soil cohesion (O'Connell et al., 2007). This in turn increases soil health and productivity. The ecological benefits of NFM are generally uncontested (Forbes et al., 2015; Hankin et al., 2017; Janes et al., 2017).

There are also anthropogenic benefits to NFM implementation. Research by Short et al. (2018) showed that the public and decision makers felt more positively towards NFM than hard engineering flood solutions due to the aesthetic qualities of NFM interventions. They were generally thought to be more aesthetically pleasing and people expressed preferences for measures that were designed to blend in with landscape over time. Moreover, setting up NFM schemes requires cross disciplinary collaboration between landowners, farmers, river managers, government bodies, hydrologists, modellers, contractors, and the public as there are multiple competing interests and uses for land and rivers. As more and more NFM schemes are implemented across the UK, multiple authors have cited improved collaborative relationships and catchments partnerships set up to implement and manage NFM schemes as one of the persistent benefits of NFM (Garvey & Paavola, 2021; Short et al., 2018; Wingfield et al., 2019).

However, competition for space is one of the major barriers to the uptake and implementation of NFM. It has been found that individual NFM interventions do very little to reduce flood peaks. The best way to gain maximum benefits from NFM is by using a suite of different NFM interventions in a scheme across the catchment (Parrott et al., 2009) which naturally takes up a lot of space. NFM interventions that are 'space expensive' are afforestation, generating online and offline storage ponds, and (arguably) changing land management practices and reducing livestock density. NFM is most often recommended in upland headwater and rural catchments due to the demand for space but can be controversial because in some cases NFM implementation would mean replacing economically productive land with NFM features. Furthermore, many NFM features, such as large woody debris, leaky dams, bunds, and storage ponds are designed to push or pool water in controlled local floods. This causes increased flood risk upstream to reduce flood risk downstream. Choosing areas that can safely be flooded for periods of time is problematic and these plans are often met with opposition. Some economic incentives have come to that support landowners in contributing or implementing NFM on their land by compensating for space lost. These subsides aren't always standardised or sufficient to cover the cost lost in potential profits of previously productive land.

Because the risk is much higher for landowners and farmers to adopt NFM schemes (i.e., a possible loss of productive land or a responsibility to monitor and care for the new installation), they are generally more hesitant to adopt NFM than decision makers (Bark et al., 2021). At the moment, these hesitations are well founded as there is currently no standardised format as well as general disagreement concerning responsibility for funding, maintaining and monitoring NFM schemes (Bark et al., 2021; Wells et al., 2020). This can make it difficult to obtain funding to implement schemes as it is not always clear which funding streams are available and how to qualify for them. Furthermore, disputes over long term responsibility can understandably lead to resistance to NFM creation. Navigating these relationships and agreements has been cited as another major barrier to NFM uptake (Garvey & Paavola, 2021). When successful, setting up cross disciplinary working relationships can be an additional benefit of NFM, but they are difficult and time consuming to establish and often requires a person to and spear head a coordinating role. Garvey & Paavola, (2021) specifically mention that community involvement often complicates these relationships due to competing interests. Further compounding these issues is an evidence base that is broad and in some cases contradictory due to the fact that NFM schemes need to be designed on a case-by-case basis (Wells et al., 2020). A particular gap in the NFM evidence base is post-implementation monitoring schemes which is often due to restrictions in budgets and a lack of funding. An increase in reliable monitoring schemes after implementation could be one of the greatest services to the NFM evidence base by providing more reliable evidence. Funding structures may be required to accommodate this change.

2.4 Natural Flood Management in the context of groundwater flooding

The vast majority of the NFM evidence base is founded on research conducted in surface water-dominated catchments where floods are caused by the convergence of multiple surface runoff inputs to the river channel. As a result, the application of NFM in groundwater-dominated catchments has been highlighted as a one of the key knowledge gaps in the NFM evidence base, in acknowledgement that the flow pathways and processes present in groundwater-dominated catchments are significantly different to those found in catchments with fluvial floods. This can be demonstrated by the difference in Base Flow Index (BFI) (Gustard et al., 1992) values for the River Lambourne (a typical chalk stream) and the River Dee in Scotland which has been used as an NFM experimentation catchment (Iacob et al., 2017). BFI measures the proportion of total channel flow contributed by groundwater sources. Belford Burn has a BFI of 0.43 (Fry & Swain, 2010) and the River Lambourne has a BFI of 0.98 (Gustard et al., 1992). This is further demonstrated in Figure 8 below, showing the difference in river regime for the two example rivers for the year 2014.

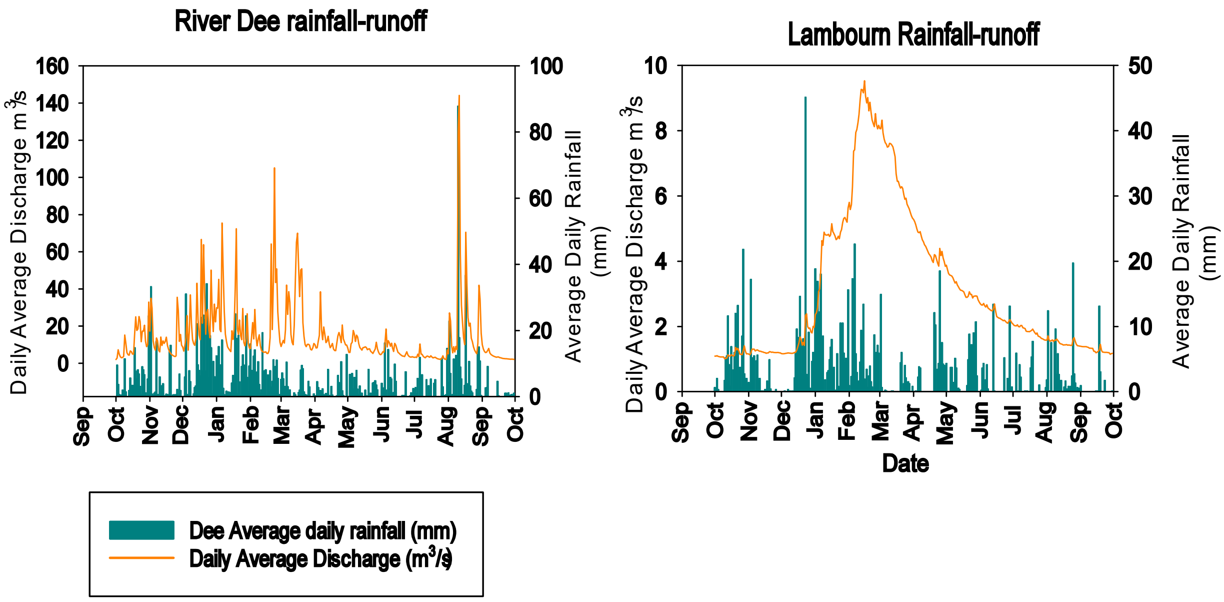


Figure 7 Comparison of hydrographs from a flashy catchment (left) and a groundwater-dominated catchment (right). The River Dee at Mar Lodge (Aberdeenshire) demonstrates a highly responsive hydrograph, with multiple sharp peaks. The Lambourn at Shaw (West Berkshire) has a highly seasonal annual hydrograph.

Figure 8 shows that the River Dee at Mar Lodge has a quick response to rainfall inputs, with flashy peaks in discharge that are roughly synchronised with rainfall. Considering this is a model NFM-appropriate catchment, it is in sharp contrast to the River Lambourne at Shaw which has the smooth annual hydrograph typical of most chalk streams. There are small discharge peaks in response to rainfall inputs, but this does not disrupt the strong groundwater dominance of the flow regime. Therefore, groundwater catchments typically transfer a large proportion of water below the ground surface. Of the 12 main NFM techniques summarised by Lane (2017), eight of them rely on managing surface water. Where most of the water transfer throughout the catchment occurs below the ground surface, these measures may have limited effect (discussed further in Chapter 3).

As discussed in section 2.2, the drivers of groundwater flooding may also reduce the efficacy of NFM under the conditions that are required to generate a groundwater flood. One of the primary goals of NFM is to increase the storage capacity of a catchment and then to release that water slowly to generate a smoother and more elongated flood hydrograph (Barber & Quinn, 2012; Lane, 2017; Mclean et al., 2013). Reductions in surface runoff flood flows are most effective in areas where rapid runoff production occurs (Naef et al., 2002). Therefore, Chalk catchments inherently have the key river regime properties that NFM methods aim to produce due to the buffer effect caused by the large storage capacity of chalk aquifers. Additionally, long periods of rainfall are required to raise the water table to the surface before flooding occurs. An example of this was the exceptionally wet winter of 2000 to 2001 where rainfall was 166% the long-term average over an 8 month period (Marsh & Dale, 2002). According to Marsh and Dale (2002) a large proportion of the damage caused during this event was due to groundwater emergence at springs and dormant winterbournes in normally dry areas of human development. It is during sustained heavy rainfall periods such as this that NFM methods focused on increased storage are far less effective. This is because prolonged rainfall doesn't allow time for stores such as bunds, ponds and soils to drain. In a Chalk bedrock context, full ponds are unlikely to be able to drain into saturated bedrock causing them to fill up over time. When these storage units are full, they do not deliver their flood benefits (Salazar et al., 2012). Because of the type of rainfall events that cause groundwater-dominated floods (i.e., sustained heavy rainfall that caused groundwater recharge), NFM methods that increase catchment storage may not be beneficial.

Nonetheless, when water tables are high, this contributes to surface water generation as groundwater emergence and elevated discharge (Lamontagne et al., 2014; Robins & Finch, 2012). Figure 8 is generated via an informal flood database generated by combining observed flood events recorded by the Environment Agency and flood events recorded in the Chronology of British Flood Events by The University of Dundee (British Hydrological Society, 2022). What it shows is that the majority of recorded flood events in chalk regions are still caused by channel bank overtopping, with the second majority due to groundwater emergence. Therefore, it is likely that NFM strategies that are concerned with manipulating conveyance of water both in channel and on the flood plain will still be effective. Theoretically, as water tables rise the volume of surface water increases, meaning these measures become more active as a flood progress. Because NFM interventions are tailored to fit the specific sources and flood water, it follows that NFM schemes in groundwater catchments will focus on different combinations of interventions than those found in surface runoff-dominated catchments, depending on the key properties of chalk catchments. It is therefore important to identify the morphological and hydrological features that affect groundwater recharge and the production of overland flows (increasing the probability of channel bank exceedance), to guide future NFM strategies in catchments dominated by groundwater processes.

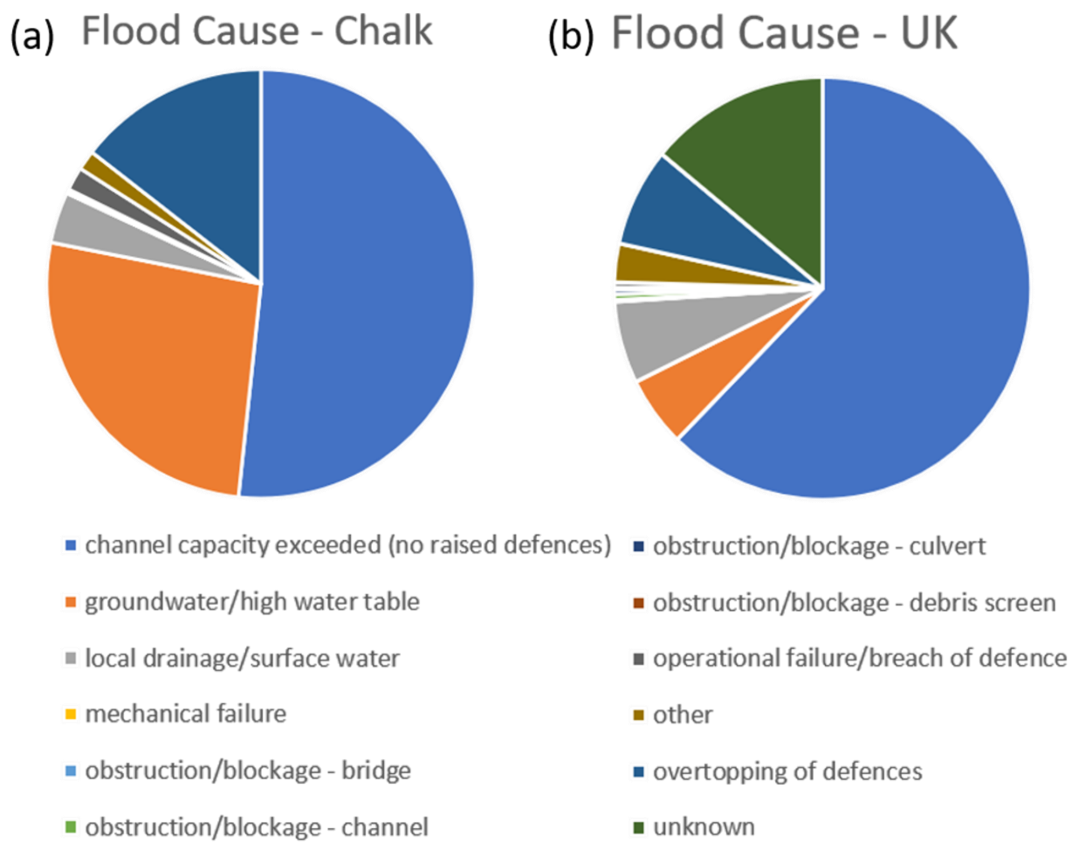


Figure 8 Pie charts which demonstrate the causes of historical floods on average across areas underlain by chalk geology (a) compared to the average flood cause for the entirety of the UK (b).

A review of the literature demonstrates that there is currently very little research that focuses specifically on testing, modelling, or applying Natural Flood Management in groundwater dominated chalk streams, despite having been repeatedly identified as a key gap in the NFM evidence base. Given that there are key differences in the hydrological function of groundwater-dominated catchments compared to the ‘flashy’ catchments in which NFM has been shown to be effective, it follows that the current NFM evidence base cannot be easily be applied to groundwater catchments. There is currently very little evidence for or against the application of NFM in chalk catchments. This is important given that a paradigm shift in flood management philosophy favours funding streams for NFM schemes. To ensure that groundwater floods are managed properly and effectively, considerable further research is required in this area. This thesis aims to fill some of these research gaps as outlined in Section 1.2.

Chapter 3 Exploring the capability of Natural Flood Management Approaches for flood reduction in groundwater-dominated chalk streams

3.1 Introduction

The vast majority of the NFM evidence base is founded on research conducted in surface water-dominated catchments where floods are caused by the convergence of multiple surface runoff inputs to the river channel (Dadson et al., 2017; Lane, 2017; The Environment Agency, 2017). As a result, the application of NFM in groundwater-dominated catchments has been highlighted as one of the key knowledge gaps in the NFM evidence base, in acknowledgement that the flow pathways and processes present in groundwater-dominated catchments are significantly different to those found in catchments with fluvial floods. NFM is a process-based approach, meaning that each NFM scheme is designed by matching flow pathways, landscape features and sources of flood waters that contribute to peak flows to specific NFM interventions that tackle those issues. Because of this, NFM interventions can be categorised according to the processes that they manipulate: 1) the reduction of rapid runoff generation, 2) increasing catchment water storage, and 3) strategies to reduce the conveyance of water downstream (Dadson et al., 2017; Lane, 2017; Pitt, 2008). This is an important distinction because it allows specific sources of flood waters to be linked to specific solutions in the process of NFM design. For example, many arable fields suffer from sediment loss due to excess rapid overland flow. In this case, NFM interventions would focus on interventions that reduce runoff generation and intercepting and storing water. Sediment trapping and storage as well as increased surface roughness to break up and slow the flow of surface runoff could be achieved by using winter cover crops or across-slope tillage. As such, NFM schemes are often tailor-made to each application scenario, and it is important that the features and water transfer processes of the catchment where it is proposed to be implemented are first established.

Groundwater catchments typically transfer a large proportion of water below the ground surface (Sear et al., 1999; Berrie, 1992). Groundwater flooding occurs when rainfall recharge causes the groundwater level to rise, in turn increasing groundwater inputs into river systems and causing groundwater emergence in topographic low points, winterbournes and activating springs (Lamontagne et al., 2014; Naughton et al., 2018). Of the 12 main NFM techniques summarised by Lane (2017), eight of them rely on managing surface water (the remaining four concern in-channel interventions). However, if most of the water transfer throughout the catchment occurs below the ground surface, these measures may have limited effect (Figure 10). Because NFM interventions are tailored to fit the specific sources and flood water, it follows that NFM schemes in groundwater catchments will focus on different combinations of interventions than those found in surface runoff-dominated catchments (Figure 10), depending on the key properties of chalk catchments. It is therefore important to identify the morphological and hydrological features that affect groundwater recharge and the production of overland flows (increasing the probability of channel bank exceedance), to guide future NFM strategies in catchments dominated by groundwater processes.

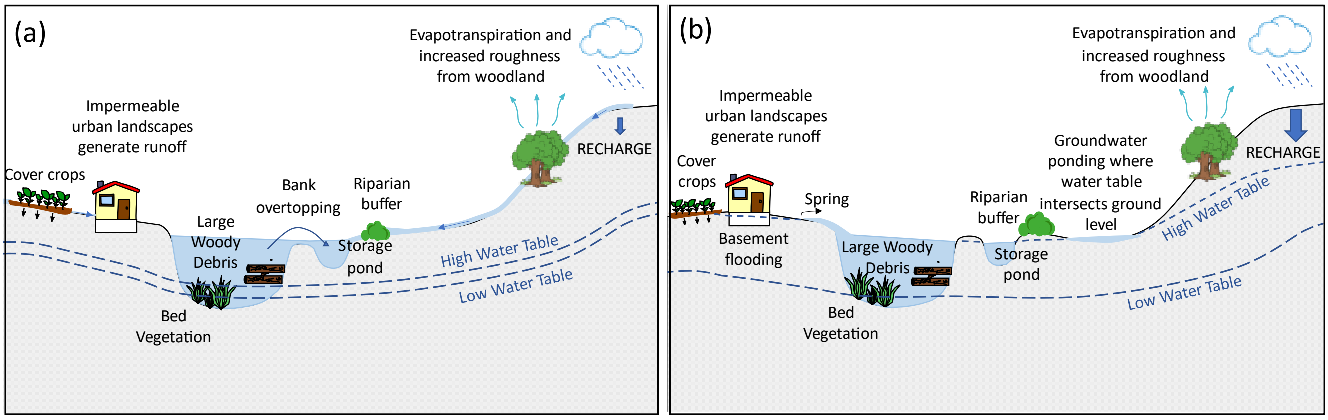


Figure 9 The processes of flooding in an impermeable upland catchments (a) and a permeable chalk catchments (b) along with common NFM interventions to demonstrate how groundwater dominance in flood production may impact the efficacy of NFM (Barnsley et al., 2021).

This study is intended as a screening process for NFM in groundwater catchments by grouping catchments according to hydrological properties and matching them to NFM interventions that specifically tackle these flow pathways. To do this, we quantify the relationships between hydrological variability and key morphological characteristics that are amenable to NFM for 198 catchments with chalk bedrock in the South East of England. We use these results to classify the catchments, infer flow pathways, and make suggestions for the most appropriate NFM strategies for these river basins. Because NFM schemes must be designed on a case-by-case basis for the greatest effectiveness, this is intended as a broad scale screening process to narrow down options, and not as a comprehensive guide for choosing NFM interventions in all chalk stream catchments.

3.2 Materials and Methods

3.2.1 Study area and catchment selection

Chalk groundwater-dominated catchments were first identified using topographic and geological datasets. Topographic catchment boundaries were provided by the Centre for Ecology and Hydrology National River Flow Archive (NRFA) (Fry & Swain, 2010). A bedrock map (BGS 625k) from the British Geological Survey (Smith, 2009) was used to identify catchments that were underlain by chalk bedrock. To reduce uncertainty due to differing groundwater transfer processes and because of the global rarity of chalk stream river systems, we focused on chalk groundwater-dominated river systems, excluding limestones or Permo-Triassic sandstones. We selected catchments with at least ≥ 70% of the catchment within the chalk bedrock, and with gauging stations within 5 km downstream of the chalk bedrock (determined via the buffer tool in ArcGIS and visual inspection). Using these criteria, a total of 198 catchments were available for analysis, located predominantly in the South East of England (Figure 11).

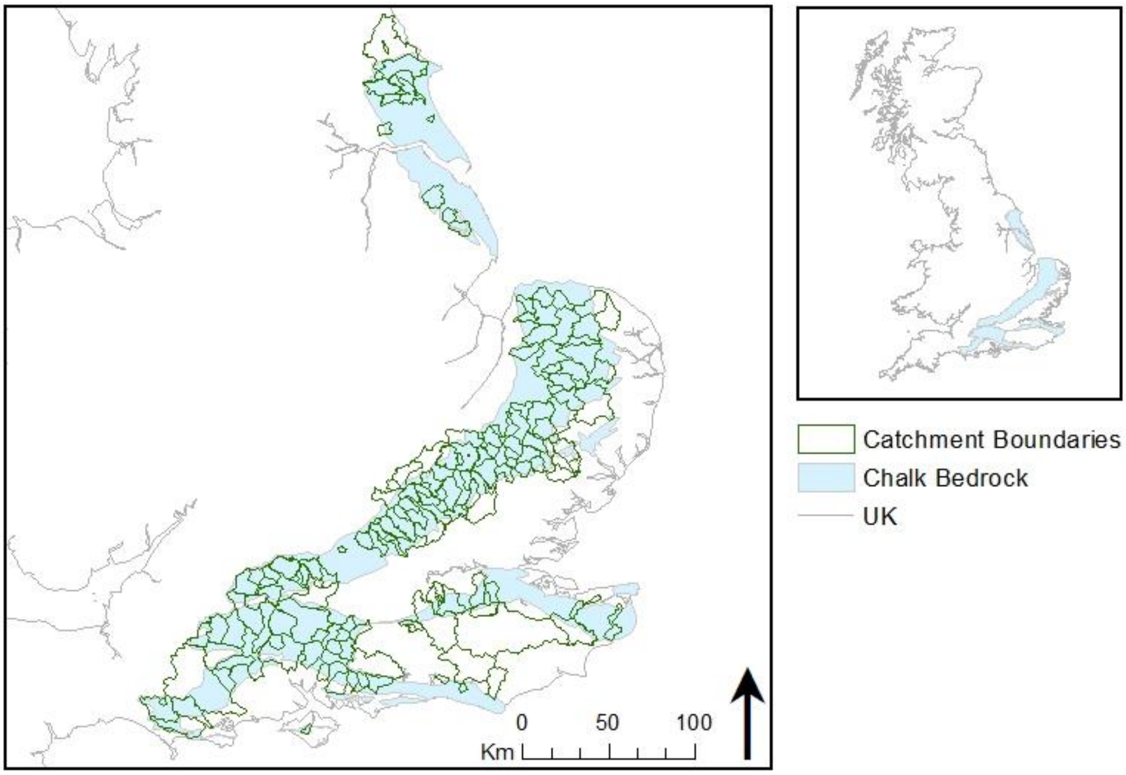


Figure 10 Location of the 198 catchments included in this study underlain by chalk bedrock. Catchment boundaries are from the National River Flow Archive and the bedrock map is from the British Geological Survey.

3.2.2 Data Analysis

To relate hydrological variability to catchment morphological characteristics, we compiled and analysed the covariation among four key hydrological variables and twenty-one variables quantifying the physical catchment properties. Details and data sources are found in Table 2.

3.2.2.1 Hydrological variables

All hydrological variables were derived from the Centre for Ecology and Hydrology UK National River Flow Archive (Fry & Swain, 2010). Average discharge (Q_{mean}) and maximum recorded discharge (Q_{max}) are among the most basic hydrological metrics used to characterise the hydrological regime. The Base Flow Index (BFI) (Gustard et al., 1992) measures the proportion of streamflow from groundwater contributions. This is relevant to NFM implementation because high BFI values are related to stable flows and limited surface runoff generation and contributions to streamflow. Conversely, the Richard-Baker Flashiness Index (Baker et al., 2004) (RBFI) measures the sensitivity of a streamflow to rainfall inputs. Therefore, high RBFI values indicate significant sources of runoff resulting in spate conditions. As mentioned previously, understanding the processes by which water is transferred throughout the catchments is essential to NFM design. Chalk streams are often characterised and defined by features such as long times to peak, high base flow domination and a lack of spate conditions (O'Neill & Hughes, 2014). However, large ranges in BFI and RBFI values within the chalk stream sample demonstrate that there is major spatial variation in chalk stream properties. These metrics will help characterise chalk catchments according to flow variability, average flows, the short-term response of flow to sharp bursts of rainfall, groundwater contributions to the flow regime, and (indirectly) the rate of recharge and runoff production. This helps inform which NFM interventions will be most suitable based on whether water transfer occurs predominantly above or below the ground surface. Details of index calculations are provided in Table 2.

3.2.2.2 Physical catchment properties

We selected 21 physical variables that directly influence hydrology and that have explained variations in catchment hydrology in other studies (Al-Saady et al., 2016; Ascott et al., 2017; Baker et al., 2004). This included the percentage cover of 9 land uses (arable land, broad leaved and coniferous woodland, grassland, heathland, urban, suburban, marshland and inland rock) from the 2015 Land Cover Map (NERC & CEH, 2017) (LCM 2015). Heathland, grassland, and marsh land covers are made up of sub-categories of each classification respectively (i.e., all separate grassland types are combined into a new homogenous 'grassland' classification). Combinations of sub-categories to generate the three new classes were done as specified in Appendix 1 of the LCM2015 documentation to generate more optimum data distributions. The hydrological impact of land cover is well documented in the literature (Table 2) and is relevant to NFM because land cover directly impacts flow pathways and consequently the choices of NFM interventions that may be suitable. Additionally, land use can inform the amount of space available for NFM application to inform what is possible. Large quantities of storage ponds, controlled flood plain zones and afforestation may not be suitable NFM interventions in regions of arable land due to the need to preserve economically productive space, whereas other interventions like winter cover crops, hedge edges and no-till farming may be more suitable. Percentage cover of 6 soil types (bypass flow common, bypass flow uncommon, bypass flow very uncommon, bypass flow variable, slowly permeable and impermeable) were classified according to the hydraulic conductivity in the Hydrology of Soil Types (Boorman et al., 1995) (HOST). This is because hydraulic conductivity can directly dictate the efficiency of aquifer recharge and surface runoff generation. Soil saturated hydraulic conductivity has been identified as one of the key features that dictated chalk stream river regime and flood response (Ascott et al., 2017). It is therefore important to understand the key hydrological processes in the catchment which will in turn be useful to inform the choice of NFM interventions. Topographic catchment shape and drainage density were included because they influence the rate of propagation of water through the catchment and river channel network (Ogden et al., 2011; Strahler, 1968 - pg. 304). Bedrock transmissivity and a proxy for aquifer abstraction rates were included because they provide information about how water propagates through the sub surface of the catchment which in turn influences streamflow response (Allen et al., 1997; MacDonald & Allen, 2001). Transmissivity values of the chalk bedrock vary between 230 m^2/day to 2600 m^2/day (MacDonald & Allen, 2001). Catchments where transmissivity is low have reduced rates of recharge, subsurface water transfer, and reduced groundwater contributions to channel flows relative to regions with high transmissivity bedrock (MacDonald & Allen, 2001). The hydrological influence of each physical catchment variable is included in Table 2, as well as details of their calculation.

Table 2 Equations and methodology of variables compiled for the response and explanatory databases for the redundancy analysis.

Variable	Equation	Description and influence on flow
Mean discharge (Qmean)	$\frac{\sum Q}{n}$ n = days in record	The average quantity of water in the river channel. Gives an indication of the discharge under normal conditions from the NRFA (Fry & Swain, 2010).
Maximum recorded Discharge (Qmax)	Q_{Max}	Maximum discharge capacity of catchments at the gauging site during high flows from the NRFA (Fry & Swain, 2010).
Richard-Baker Flashiness Index (RBFI)	$RBFI = \frac{\sum_{i=1}^{n} \lvert q_i - q_{i-1} \rvert}{\sum_{i-1}^{n} q_i}$ q = dimensionless measure of discharge I = time n = number of discharge measurements	Measures the absolute daily fluctuations in streamflow, divided by the sum of all stream flow for the time series length (Holko et al., 2011). Values range between 0 and 1 Values near 0 represent stable flow and those close to 1 represent highly changeable flows and spate conditions (Baker et al., 2004).
Base Flow Index		BFI measures the proportion of river runoff derived from stored sources (Fry & Swain, 2010; Gustard et al., 1992).
Variable	**Equation**	**Description and influence on flow**
Catchment area (Ca)	-	Watershed boundary shapefiles from the NRFA (Fry & Swain, 2010) facilitate calculations for other catchment properties. Smaller catchments are associated with steeper hydrograph rising limbs due

		to reduced catchment complexity (Sabo et al., 2010; Sherman, 1932).
Form factor (Rf)	$Rf = \frac{Ca}{Bl^2}$	Measures the geometric shape of the catchment. Circular catchments (Rf = 0) have with steep hydrograph peaks (Strahler, 1968 - pg, 304).
Drainage Density (Dd)	$Dd = \frac{StL}{Ca}$	High drainage densities are linked to drainage efficiency and high peak flows (Ogden et al., 2011).
Channel Slope	m/m	Calculated from a raster layer of SRTM 30m Digital Elevation Model (Farr et al., 2007) in ArcGIS using the zonal statistics function.
% Land Cover Type	$\frac{Landuse\ area}{Ca} \times 100$	Land use effects on hydrology (NERC & CEH, 2017).
	Arable Land and Horticulture	Reduced peak flows (O'Connell et al., 2007).
	Broadleaf Woodland	Reduced peak flows (Nirupama & Simonovic, 2007).
	Coniferous Woodland	Reduced peak flows due to large leaf surface area (Nirupama & Simonovic, 2007).
	Grassland	No overall influence (Alaoui et al., 2011).
	Heathland	No overall influence– the effects of vegetation are counteracted by shallow soils and low storage capacity (Granged et al., 2011).

	Urban	Increased peak flows–- impervious surfaces and drainage systems (Miller et al., 2014).
	Suburban	Increased peak flows–- impervious surfaces and drainage systems (Miller et al., 2014).
	Marshland	
	Inland Rock	Increased peak flows -imperviousness.
% Soil cover type	$\frac{HOST\ Soil\ Type}{Ca} \times 100$	The Hydrology Of Soil Types (HOST) from CEH (Boorman et al., 1995).
	Bypass Flow Common	Permeable (Vertical saturated hydraulic conductivity > 10 cm/day-1)
	Bypass Flow Uncommon	Permeable (Vertical saturated hydraulic conductivity > 10 cm/day-1)
	Bypass Flow Very Uncommon	Permeable (Vertical saturated hydraulic conductivity > 10 cm/day-1)
	Bypass Flow Variable	Semi-permeable (Vertical saturated hydraulic conductivity 0.1 – 10 cm/day-1)
	Slowly Permeable Soils	Semi-Permeable (Vertical saturated hydraulic conductivity 0.1 – 10 cm/day-1)

	Impermeable	Impermeable (<0.1 cm/day-1 Vertical saturated hydraulic conductivity)
	Peat	Semi-permeable (Vertical saturated hydraulic conductivity 0.1 – 10 cm/day-1) (Wong et al., 2009).
Transmissivity (m2/day)	$$Transmissivity = \frac{ga^3}{12v}$$ g = acceleration due to gravity a = area v = kinematic viscosity of the fluid	The rate at which water passes through the chalk bedrock (Allen et al., 1997; MacDonald & Allen, 2001).
Abstraction score	Subjectively assigned an arbitrary ‘abstraction score’ based on the flow regime description on the ‘gauging station info’ in the NRFA. Scores: flow added, natural flow, minor, moderate and major reduction of flows due to abstraction.	Quantifies influence of abstraction on river regime (Fry & Swain, 2010).

3.2.3 Statistical analysis

3.2.3.1 Redundancy Analysis

This study used Redundancy Analysis (RDA) (van den Wollenberg, 1977) to characterise and explain the variation in hydrological properties in relation to physical properties. RDA is an asymmetric ordination method whereby the variation in one set of (explanatory) variables is used to directly explain the variation in another set of (response) variables. Essentially a combination of multiple regression and principal component analysis, RDA generates a matrix of the fitted values of all response variables which are then subjected to a principal component analysis. Linear combinations of explanatory variables (physical catchment properties) that best explain the variation in the response variables (hydrological properties) are sought by the model in successive order. The main advantages of using RDA over principal component analysis in this context are that variance in the response variables is attributed to the explanatory variables, and presence or absence of a relationship between specific x and y variables can be tested (van den Wollenberg, 1977). It can therefore be used to directly link hydrological traits of chalk streams to the presence or absence of specific physical features enabling more targeted NFM scheme design.

All analyses were undertaken in the R environment (version 3.6.1) (R Core Team, 2019). After compiling the variables as outlined in Table 2, all variables were transformed using a Box Cox transformation, centered and scaled to reduce the influence of outliers and place variables on a common scale for the RDA model (Box & Cox, 1964).To identify the explanatory variables that best describe the co-variation of the hydrological variables, a preliminary redundancy analysis (RDA) model was initially run using the 'rda' function of the 'vegan' package in R (Oksanen et al., 2019). This global model, using all 21 catchment variables, was subjected to model validation. To achieve a parsimonious model containing important physical explanatory variables the global model was subjected to a forward stepwise procedure using the 'forward.sel' function of the 'Packfor' R package (Dray et al., 2016 - pg. 48). This process selects the model with the combination of variables with the highest R^2 and *p* value (Legendre & Legendre, 2012 - pg. 178). The remaining physical catchment variables after the stepwise procedure are those that directly correlate with and explain the variation in hydrologi–al regime in chalk streams whilst maintaining the highest explanatory power (R^2). Catchments were then plotted as a point on a biplot according to their RDA coordinates. The resulting forward selected RDA model was then subjected to a validation process including ANOVA tests of the significance of the relationships identified in the parsimonious model and the number of significant axes in the model using 1000 permutations. The covariance of the selected physical catchment variables in the model was ascertained using the Variance Inflation Factor (VIF).

3.2.3.2 Catchment classification

Cluster analysis was used to group catchments with similar river regimes according to catchment RDA coordinates. Catchments with similar combinations of physical catchment property variables are located near each other on an RDA biplot (have similar RDA coordinates). Before subjecting the data to cluster analysis, the data's tendency for clustering was established using the Hopkins Statistic using the 'get_clust tendency' function of the 'factoextra' package in R (Lawson & Jurs, 1990). Four hierarchical clustering methods were compared for their suitability to the dataset according to two distance measures (cophenetic correlation and the Gower statistic). Cophenetic correlation measures the degree of agreement between the original unmodeled pairwise distances and the pairwise distances in the dendrogram. A high positive correlation indicates that pairwise distances have been preserved (Saraçli et al., 2013). The Gower statistic is the sum of squared differences between the dissimilarity matrix and the cophenetic distance and is calculated using dendrogram hierarchical partition (Borcard et al., 2011; Gower, 1971). The clustering algorithms compared were single, complete, and average linkage agglomerative clustering and Ward's minimum variance clustering (Borcard et al., 2011). The optimum number of clusters was established via a Mantel correlation. Here, the original distance matrix is compared to binary matrices computed from the dendrogram being cut at multiple different levels for different numbers of cluster allocations (Borcard et al., 2011). The optimum number of clusters is where the Mantel correlation is highest.

The uncertainty in the allocated clusters was estimated using silhouette widths. This measures the degree of membership of an object to its allocated cluster by comparing the average distance of an object to all other objects in the same cluster, to the average distance between it and all the objects in the next closest cluster (Rousseeuw, 1987). Accordingly, high silhouette width values indicate that that catchment has a high degree of membership in that group. Catchments with negative silhouette width values can be assumed to have been misclassified.

Once the clustering allocations were validated using the pairwise distance measures, the catchment groupings were mapped and used to describe the variation within chalk stream hydrology and flow pathways, and the potential for the application of NFM for each group was assessed according to its specific physical and hydrological qualities.

3.3 Results

3.3.1 Redundancy analysis

The stepwise redundancy analysis revealed that the combinations of the following catchment properties significantly explained the co-variation of hydrological variables ($p \leq 0.001$): area, uncommon bypass flow, impermeable soils, slowly permeable soils, station elevation, form factor, and urban land use (Table 3). The adjusted R^2 values, representing the proportion of hydrological variance, which is explained by the physical catchment properties, were 0.682 for the global model and 0.675 for the reduced model. Only the first two axes were used for analysis (axes 1: 77.4%, axes 2: 35.9%) as the third axis and beyond were statistically insignificant. Variance Inflation Factor (VIF) values (Table 4) reveal that the remaining 9 variables have very little collinearity (VIF values <5). Despite ‘uncommon bypass flow’ and ‘slowly permeable soils’ being mildly collinear, they were both retained because removal of either caused a substantial drop in the explanatory power of the model. The 15 catchment variables removed via the forward selection process did little to reduce the Adjusted R^2 value suggesting that the discarded variables mostly generated noise.

Table 3 Explanatory variables chosen during the forward selection process.

Additionally, their comparative explanatory power (adjusted R^2) and significance (F statistic and p values). The explanatory variables represent the most parsimonious model and explain the most variation in the hydrological response dataset.

Variable	**Order**	**R^2**	**Cumulative R^2**	**Adjusted cumulative R^2**	**F statistic**	**P Value**
Area	2	0.357	0.357	0.353	108.6	0.001
Uncommon Bypass Flow	18	0.231	0.588	0.584	109.3	0.001
Impermeable soils	22	0.034	0.622	0.584	17.5	0.001
Slowly permeable soils	21	0.037	0.659	0.652	20.8	0.001
Station Elevation	1	0.02	0.669	0.660	5.8	0.001
Form Factor	4	0.010	0.679	0.669	6.1	0.001
Urban	14	0.007	0.686	0.675	4.43	0.001

Table 4 VIF values of the explanatory variables kept in the parsimonious RDA model.

VIF values exceeding 10 indicate collinearity between variables.

	Area	**Uncommon bypass flow**	**Impermeable soils**	**Slowly permeable soils**
VIF	1.143	4.625	1.691	4.482
	Station Elevation	Form Factor	Urban	
VIF	1.248	1.029	1.057	

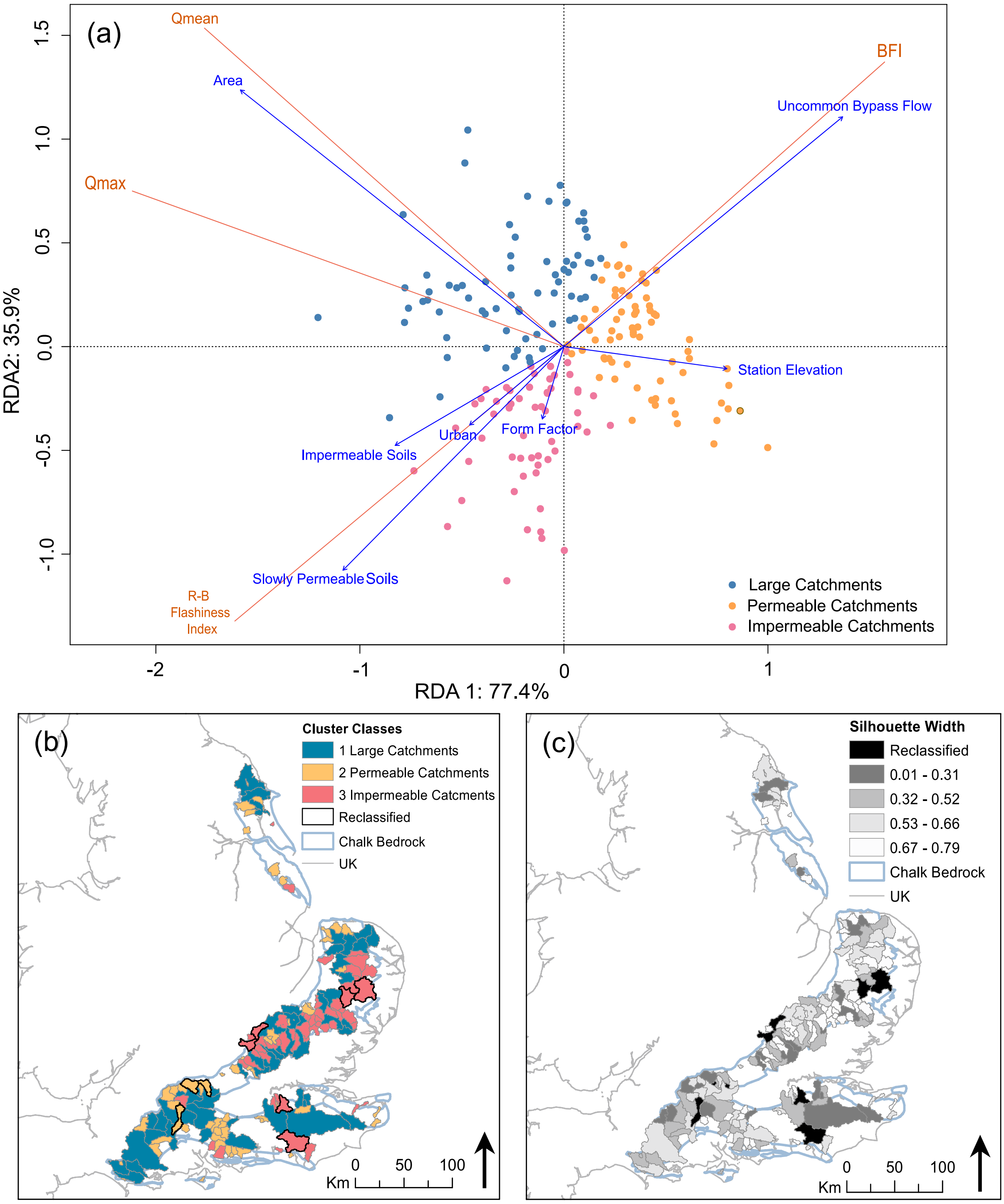


Figure 11 (a) Biplot showing catchment locations along two RDA axes. (b) The catchment classifications mapped spatially. (c) The uncertainty of catchment classification according to silhouette widths.

Dark orange vectors represent hydrological variables blue vectors are the catchment properties, with points for catchments placed relative to the vectors based on their individual values for catchment properties. Misclassified catchments are presented in their reclassified grouping and outlined in bold. Misclassified catchments (<0) were reclassified into their nearest neighbour alternative classification.

3.3.2 Clustering and cluster validation

Catchments were grouped into three clusters using the average linkage hierarchical clustering algorithm. The data's tendency for clustering was established prior to this via the Hopkins Statistic (0.752; significant = >0.5 and <1). Average linkage hierarchical clustering was selected out of the four algorithms because it returned the highest cophenetic correlation and smallest value for the Gower distance (Table 5). Despite four clusters being identified as the optimum number of clusters for this dataset according to the Mantel correlation (Fig. 4), three clusters were used because the fourth was not associated with any vectors on the biplot, making it difficult to interpret. Silhouette widths were used to quantify and map the uncertainty in catchment group allocations (Fig 3c). An average silhouette width of 0.50 indicates that catchments were generally classified correctly with all misclassifications occurring in group 1 (Fig 4). Silhouette widths below 0.31 were considered uncertain due to being close to the decision boundary and catchments with silhouette widths below 0 were misclassified (Borcard et al., 2011 - pg. 70). A reduction in average silhouette width from 0.53 with four clusters to 0.5 with three clusters indicates that group cohesion is slightly reduced by this decision. To mitigate against this, the nine misclassified catchments (Figure 13) were reclassified and displayed as their nearest neighbour alternative classification in Fig 3.b.

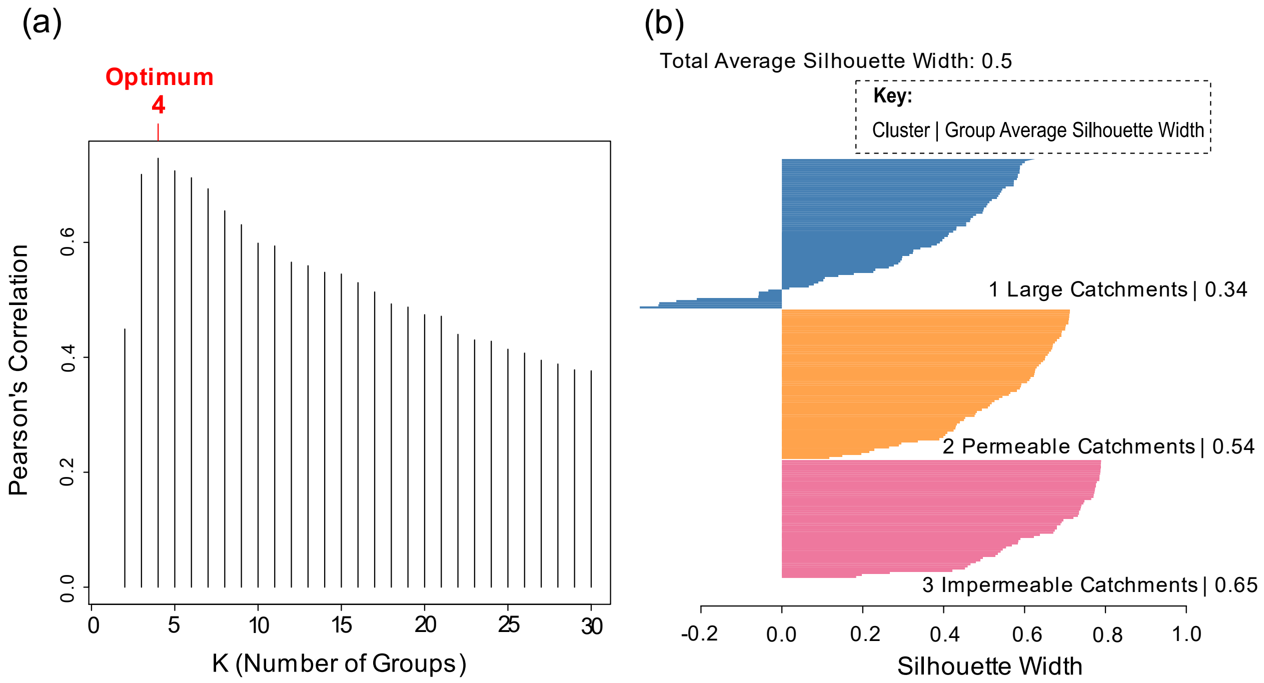


Figure 12 (a) The optimum number of average linkage clusters according to the Mantel statistic. (b) Silhouette plot of the final three groups from the average linkage agglomerative clustering. This figure demonstrates that points are generally correctly classified, with all 9 misclassifications occurring in cluster 1 – large catchments.

Table 5 Gower distance and cophenetic correlation results for all four hierarchical clustering methods for comparison.

A high cophenetic correlation indicates a strong relationship between the distance matrix and the cophenetic matrix describing the dendrogram split where each point is clustered differently. A lower Gower distance indicates as acceptable clustering algorithm

Single Linkage	**Complete Linkage**	**Average Linkage**	**Ward's clustering**
Gower distance	30,878.360	62,837.240	6,538.116
Cophenetic correlation	0.757	00.748	0.802

3.4 Discussion

The explanatory power of the parsimonious RDA model is within the acceptable range for RDA models that characterise hydrological variation (Gerisch, 2011; Mazouz et al., 2013; Pham et al., 2008). The model has been used to group catchments with similar physical catchment properties and river regime properties using their coordinates from the RDA plot. Thus, the cluster classifications have been used to infer catchment typology and hydrological conditions, including rates of aquifer recharge and rapid runoff generation. The cluster classifications are used as a screening process to identify which NFM interventions can theoretically be applied or ruled out of each catchment typology based on the dominant physical catchment properties identified by that group as shown on the RDA plot (Fig 3).

It is acknowledged that this approach relies heavily on the partitioning of catchments into groups. Hence care was taken to ensure that uncertainty in cluster allocation was reduced by checking the data's tendency to cluster. The number of clusters and the clustering algorithm selected made the most statistical sense were selected (section 3.2). However, uncertainty in cluster allocation cannot be removed entirely and 13.6% of the sample had 'uncertain' group allocations (Fig. 3c). It is understood that these catchments share traits that would allow them to be comfortably grouped in to two of the three groups and are therefore understood to be 'intermediate' catchments that do not easily fit in to a single classification. In these cases, the combined traits of the two catchment classifications should be taken into account when selecting NFM options for these catchments (alternative groupings for highly uncertain catchments are provided in Appendix A). Catchments that have been reclassified can be confidently allocated to their group.

3.4.1 Group 1: Large catchments

Group 1 catchments have high Q_{mean} and Q_{max} values which are explained by their large size (Figure 12). These are the largest catchments within the sample, with topographic catchment areas ranging from 108 km^2 to 1459 km^2. Q_{max} has a strong negative correlation to station elevation, demonstrating that catchments with higher discharges tend to be those closer to sea level and further downstream resulting in large water accumulation. Q_{mean}, Q_{max} and catchment area have weak correlations (shown by orthogonality) with all other variables in the model rendering it difficult to comment further.

Previous research suggests that NFM becomes less effective at reducing flooding in catchments greater than 20 km^2 (Dadson et al., 2017; Wilkinson et al., 2019). Furthermore, evidence shows that increasing the area impacted by NFM measures does not always increase the gains in flow attenuation (Lane, 2017; O'Connell et al., 2007). The lack of substantial evidence for NFM implementation at a larger catchment scale has become a barrier to the general uptake of NFM (Wingfield et al., 2019) however, it must be acknowledged that very few catchment-scale NFM schemes have been implemented (Lane, 2017; O'Connell et al., 2007). The NFM evidence base at this scale is mostly provided by risk-based predictive models (Woodward et al., 2009) which introduces computation limitations to catchment-scale NFM research and their subsequent findings (Metcalfe et al., 2017). Nonetheless, it is generally accepted that NFM is most effective for (and possibly limited to) catchments <20 km^2.

Metcalfe et al. (2017) argue that a large proportion of the benefits of NFM come from its ability to desynchronise sub-catchment flood waves which theoretically works at every catchment scale (Pattison et al., 2014). Desynchronisation is achieved by implementing NFM schemes at a small scale in carefully chosen sub-catchments which are designed to attenuate individual sub-catchment flood waves, reducing the likelihood of flood wave synchronisation. Whilst it is recognised that the flood peak reductions from this process are often small, it can be enough to prevent bank overtopping in events up to 1:100 year scale (Ferguson & Fenner, 2020). Additionally, this method is only suitable in situations where the configuration of the sub-catchments currently causes synchronised flood waves. Dixon et al. (2016) illustrate that, in some cases, NFM placement can synchronise flood waves that were previously staggered, resulting in an overall increase in flood risk. Where desynchronisation of flood waves is the goal, experimental modelling is required in the design process and prior to implementation of an NFM scheme to mitigate such risks (Hankin et al., 2017; Metcalfe et al., 2017).

As none of the catchments found in group 1 are <20km^2, the evidence is lacking to support the effective use of NFM within these river basins. However, this does not prevent these larger catchments from being broken down into multiple sub-catchments or for NFM opportunities to be identified and applied locally for point-source flooding. An example of this could be to implement bunds on a sloped field to prevent field runoff from flooding an adjacent road. In specific situations it may be suitable to investigate the use of desynchronising flood waves to reduce the incidence of bank overtopping. Such areas would be downstream river sections where multiple sub-catchments contribute flood waves and relatively small changes in river levels alter the risk of bank overtopping (Ferguson & Fenner, 2020; Metcalfe et al., 2017). Extensive research and considerable time are required to design and implement effective NFM strategies for desynchronisation (Hankin et al., 2017), so it is only recommended where combined flood waves are known to be a problem. Low drainage density of permeable chalk catchments, however, limits the opportunities for desychronisation.

3.4.2 Group 2: Permeable catchments

These catchments are the 'stereotypical' chalk catchments which are generally small with a high BFI. Group 2 catchments have river regime variability closely related to high BFI values and are associated with a large proportion of uncommon bypass flow soil types and higher station elevations (interpreted here as a higher proportion of headwater catchments). 'Uncommon bypass flow' is a classification of soils from the HOST soil classification that describes thin (aquifer within 2m), permeable and unconsolidated soils with micro and macro pores (Boorman et al., 1995). These soils have a vertical saturated hydraulic conductivity of >10 cm day^{-1} (Bell, 1985), allowing highly efficient recharge via vertical drainage into the chalk aquifer. This is linked to reduced runoff generation, limiting the potential for NFM implementation because a large proportion of the water transfer throughout the catchment occurs below the ground surface. Due to the lack of significant runoff, NFM treatments that aim to reduce runoff generation or store surface water within the catchment are highly unlikely to have a significant effect on streamflow. Examples of such interventions include winter cover crops, changes in tillage practices, lengthening drainage pathways, planting across slopes, online and offline storage ponds, wetlands, and controlled flood zones (Lane, 2017). What remains are NFM techniques that focus on in-channel interventions to reduce downstream conveyance (Lane, 2017), such as channel realignment, sustainable urban drainage systems, de-culverting covered river channels, and increasing in-channel, riparian and marginal vegetation (Caraher, 2015; Schafer, 1986). Whilst in-channel river restoration schemes such as these can significantly reduce flood peaks in small catchments (Acreman et al., 2003; Skinner & Haycock, 2005), it must be emphasised that restoration schemes and in-channel interventions deliver the best results as part of a suite of other NFM measures (DEFRA, 2004). Therefore, whilst beneficial, in-channel measures alone are unlikely to deliver the optimum impact of NFM interventions.

Despite a lack of surface runoff generation in highly groundwater dominated catchments such as those in group 2, surface water can occur due to groundwater emergence. In this case, the water table rises to intersect with the ground surface forming static pools of water in topographic low points called turloughs (Naughton et al., 2017), intermittently flowing river channels called winterbournes (Smith et al., 2003), and can activate springs in weak points and fractures in the chalk (Atkinson & Smith, 1974; Naughton et al., 2018). These phenomena generally occur after large quantities of prolonged rainfall. Previous groundwater emergence floods have been recorded after rainfall events that double and triple the long-term averages (Macdonald et al., 2012; Marsh & Dale, 2002; Naughton et al., 2017; Pinault et al., 2005). Under such conditions, NFM has been shown to be far less effective because engineered and natural stores of water such as soil storage, storage ponds, log jams and groundwater stores become full and are overwhelmed (Dadson et al., 2017; Lane, 2017). The presence of turloughs, winterbournes and springs demonstrate that water transfer throughout the catchment is not uniform across space and is dictated by the location, size, and activation of hydrogeological features such as fractures (Arnott, 2008; Bradford, 2002; Lamontagne et al., 2014). As a result, NFM schemes in these catchments will require in-depth, local knowledge to design them with sensitivity to the local hydrogeological features. We suggest that NFM interventions in this group of catchments be focused in areas where groundwater emergence occurs as winterbournes and springs to intercept or store flood flows, particularly where the resulting surface water causes disruption or damaged to property. For example, in-channel interventions such as log jams and online storage ponds could be installed in in the path of known winterbournes and springs to intercept flows when the water table is high. The potential benefits of this kind of NFM installation have not currently been tested.

For these catchments, it is suggested that NFM will have diminished effectiveness due to a lack of significant surface runoff. This limits suitable NFM interventions to mostly instream channel modifications to reduce rapid conveyance which will be less effective compared to a full suite of NFM interventions (DEFRA, 2004; Lane, 2017). In many cases, it may be more economical to map and maintain local knowledge of groundwater emergence for flood risk mapping. Previously, major flood damages were caused by urbanisation of forgotten dormant winterbournes and springs, which then activate under heavy rainfall (Marsh & Dale, 2002). These mapping efforts would also be instrumental in designing and locating potential NFM schemes near hydrogeological features such as springs and winterbournes. Therefore, effective flood mitigation measures are associated with tracking water table heights, flood warnings, flood mapping and making a concerted effort to understand spatial changes in hydrogeology. Long-term groundwater emergence and flood risk maps are required for appropriate flood planning, for identifying locations for NFM schemes and for reducing flood risk by restricting building and development on areas at risk of groundwater emergence.

3.4.3 Group 3: Less permeable catchments

Group 3 catchments are associated with high RBFI values (Figure 12), which is best explained by higher incidence of impermeable and slowly permeable soils, the presence of urban land use and higher values of form factor (indicating more circular catchment shape). These are the chalk catchments with the largest proportions of surface runoff. Higher RBFI values describe greater flow variability, steeper and higher magnitude discharge peaks. The relationship between soil permeability and rapid runoff generation is well known and documented, where impermeable soils and surfaces generate greater quantities of surface runoff and quick-flow catchment pathways (Ascott et al., 2017; Boorman et al., 1995; Griffiths et al., 2006; Holman et al., 2003; Misstear et al., 2009). Work previously performed on chalk stream catchments by Ascott et al. (2017) concluded that impermeable superficial deposits, such as those found in group 3 catchments, slow the vertical conveyance of water into the aquifers, reducing recharge and groundwater dominance in the river regime and flood response. Inversely, reduced rate of recharge and absorption of rainfall sub-surface will increase surface runoff generation.

As demonstrated by Lane (2017), a large proportion of NFM interventions work by manipulating and intercepting surface runoff pathways (Wilkinson et al., 2019). By virtue of a greater quantity of surface runoff, the full suite of NFM strategies are viable in group 3 catchments, including reduction of rapid runoff generation through soil management and increased catchment roughness, increasing catchment water storage using storage ponds, and reducing the conveyance of water downstream with in channel and river restoration strategies. This allows many different potential combinations of NFM intervention for optimising results (DEFRA, 2004) meaning that this group of chalk catchments is the most suitable for the application of NFM in the study sample.

3.4.4 Applications of NFM in chalk catchments

According to the typology of catchments generated via redundancy analysis, 3 chalk catchments in the UK (Yeading Brook West at North Hillingdon, Catchwater at Withernwick and the River Dour at Crabble Mill; Appendix 1) inherently have the physical and hydrological features best suited to the current range of NFM measures. The study sample accounts for 198 of the estimates 224 chalk streams in the UK. In the study sample, only 25 chalk catchments are <20 km^2 and of these 22 are classified as ‘permeable catchments’ limiting them to mostly in-channel NFM interventions and highly targeted NFM schemes downstream of hydrogeological features. Overall, this suggests that implementing NFM in chalk groundwater-dominated catchments is likely to have sub-optimal results compared to other catchment types (Nicholson et al., 2012; SEPA, 2012; Wilkinson & Quinn, 2010).

The findings of this analysis do not necessarily negate the use of NFM methods in chalk catchments. Where appropriate, desynchronising sub-catchment flood waves can be implemented for larger catchments classed as ‘impermeable’ by applying NFM at the local scale. NFM should also be considered on the local scale in areas where groundwater emergence as springs and winterbournes cause disruptions, or for any other known source of surface water or runoff. Additionally, the environmental benefits of NFM on water quality, aesthetic improvements, reductions in soil erosion and biodiversity are uncontested (Wingfield et al., 2019). There are proven benefits for river managers and catchment partnerships in chalk streams regions to implement NFM for river restoration, water quality and biodiversity improvements. The application of NFM is a cross-disciplinary collaborative process, so the benefits of increased communication and the formation of catchment partnerships have been argued to be another of the co-benefits (Wilkinson et al., 2019). Wingfield et al. (2019) argued that building the evidence base for NFM to irrefutability could take decades and that by hesitating to implement NFM due to a lack of current evidence means that potential benefits are lost. Minor flood benefits gained through river restoration will likely have minimal effect for large scale storms but may reduce the incidence of small scale 'nuisance floods' (Dixon et al., 2016; Ferguson & Fenner, 2020). Therefore, river restoration is advantageous to flood reduction but should not be considered the main objective unless supported by local detailed analysis. Additionally, even in groups 1 and 2 catchments, there are likely small-scale point-source locations of pluvial flooding, like flooding of fields or roads, and groundwater emergence that could be combatted with small-scale NFM schemes. However, implementation of such schemes will require better reporting and mapping of local sources of flooding.

3.5 Conclusions

The results of a Redundancy Analysis model have been used to generate a typology of chalk catchments, resulting in three groupings according to broadly similar river regimes and physical catchment properties. Using these classifications as a screening tool, the likely effectiveness of applying NFM in each of these groups has been discussed. The first class (group 1) is grouped by virtue of their larger size meaning they are likely unsuited to NFM due to NFM being most effective for catchments <20km^2. It is acknowledged that these catchments can be broken down into smaller sub-catchments, possibly to desynchronise sub-catchment flood waves. Desynchronisation is only recommended in conjunction with hydrological modelling prior to NFM design. It should also be considered that flood reductions from desychronising flood waves are most effective for smaller 'nuisance' floods rather than larger flood events. 'Permeable' catchments (group 2) are associated with smaller headwater catchments and high permeability soils. NFM interventions are less suited due to a low proportion of surface runoff processes. Large quantities of surface water can, however, be generated due to groundwater emergence at hydrogeological features such as winterbournes or springs which activate when the water table is high. Effective flood planning in these catchments is more likely to come in the form of in-channel NFM interventions, hydrogeological mapping, building, and planning restrictions and the development of groundwater emergence early warning systems. We suggest that NFM schemes in these catchments be small-scale and highly targeted to deal with runoff from activated hydrogeological features that would otherwise cause small-scale disruptions (i.e., flooding roads). Catchments classed as ‘impermeable’ (group 3) are related to the presence of impermeable and slowly permeable soils, as well as other less permeable surfaces such as urban land use. Due to this, runoff is generated, meaning that this category of catchments is the most suited to NFM in the chalk stream sample.

Overall, this study suggests that implementing NFM in chalk groundwater-dominated catchments is likely to have sub-optimal results compared to other catchment types. However, NFM implementation may be justifiable purely on the merit of the multiple environmental benefits, such as improved water quality, aesthetic improvements, reduced soil erosion, increased biodiversity, and collaboration across multiple river management bodies. This thesis provides a first order triage of the potential for NFM runoff management methods in chalk catchments. Further work in this field will need to focus on hydrological models that represent the permeability of the soils and the influence of groundwater on stream flows, detailed groundwater emergence and flood risk mapping, as well as NFM implementation studies specifically on chalk streams.

Chapter 4 Establishing the spatial extent and roughness of variable channel management for hydraulic models of the Rivers Test and Itchen

4.1 Introduction

This chapter explores the effects of rewilding river channels through reduced channel management and river restoration practices on the conveyance of flood flows in ecologically sensitive chalk streams. Given a recent change in river management philosophy which promotes the importance of habitat rewilding, river restoration efforts have become synonymous with reduced human interference and management (Prior & Ward, 2016). Policy changes reflect approaches to delivering multiple benefits for nature and flood risk management (Environment Bill 2021, Flooding Strategy 2020; Newson et al., in press) However, little is known about how a less hands-on management approach to river channels influences flood flows in chalk streams, mainly as a result of little funding for ongoing monitoring. The flood risk management benefits of re-wilding and restoration of natural river channels are often used as an argument for adopting them (The Environment Agency, 2013), despite little evidence to support this in the context of chalk streams. Natural Flood Management (NFM) is perceived as satisfying both requirements because it delivers flood reduction, as well as increased biodiversity, and improved water quality (Forbes et al., 2015; Hankin, et al., 2017; Janes et al., 2017). Recent research by Barnsley et al. (2021) shows that flood mitigation from NFM interventions in most chalk catchments are less likely to be effective due to a relative lack of surface runoff processes in catchments with highly permeable soils and rapid aquifer recharge. They suggest that in-channel NFM interventions (such as woody debris, increasing marginal and in-channel vegetation, re-meandering etc.) are among the most likely NFM interventions to deliver flood reduction benefits.

However, to date there has been no synthesis of the management techniques used for chalk rivers in relation to how they alter in-channel complexity and roughness. The roughness of the river channel is a key element in understanding the conveyance of flood flows through the river network. The aim of this chapter is to establish the spatial location of the types of management and associated Manning's roughness found on the Test and Itchen to enable parameterisation of a numerical model in Chapters 5 and 6. Specifically, this is done by 1) establishing the current range of management types used in these river systems; 2) mapping these management types across the river systems, and

3) using a combination of published literature and field observations to define Manning's roughness values. Taken together, this chapter addresses research question 2 as outlined in Chapter 1, exploring the co-evolution of management techniques, river reach complexity and bulk roughness.

England's chalk streams represent a unique habitat and hydraulic system. Traditionally they feature cool, very clear, and mineral rich water with gravel river beds which are capable of supporting a uniquely diverse ecosystem (O'Neill & Hughes, 2014). Stable flows and large quantities of nutrients provide optimal conditions for the growth of aquatic plants (maximum biomass recorded at 400g dry weight per meter square with typical levels around 200g dry weight per meter square) including Ranunculus (*Ranunculus penicillatus* and *Ranunculus calcareus)* which tend to dominate (Berrie, 1992). As well as aquatic vegetation, chalk streams support large populations of fish relative to other river types, especially brown trout, Atlantic Salmon and sea trout, making them famous hotspots for commercial fishing and angling (Berrie, 1992; Mann et al., 1989; The Environment Agency, 2013). Due to their high biodiversity and the presence of rare or important species, four of England's chalk streams are designated as international Special Areas of Conservation (SACs) and a further eight are nationally important areas of Special Scientific Interest (SSSI) (O'Neill & Hughes, 2014). Chalk streams are highly altered river systems, with centuries of modifications including the construction of sluices and multiple artificial channels for water meadows, mills and navigation as well as channel realignment and/or deepening for land drainage (Brown et al 2018; Sear et al 199; Mainstone 1999). The historical infrastructure, although now largely unused for its original purposes, remains and is an integral part of the hydraulic function of the river system whilst at the same time being valued for its cultural and historical importance (Brown et al., 2018). A major pressure on chalk streams is groundwater abstraction for civil water supply which has caused a drop in some local water levels resulting in enduring low flows (Wright & Berrie, 1987). Low flows and increased periods of dry river beds can modify the makeup of macrophyte, macroinvertebrate and fish communities, favouring species that can tolerate low flows or long periods of dry river beds (Westwood et al., 2017). Low flows can degrade ecosystems by depositing fine sediment on the channel bed smothering macroinvertebrates or by restricting fish passage throughout the river system (Solomon & Paterson, 1980; Wood & Petts, 1999). This has led to 75% of England's chalk streams to be designated 'heavily modified water bodies' in the 2008-2012 River Habitat Surveys and to be described as "in a shocking state of health" by World Wildlife Fund UK and The Environment Agency (O'Neill & Hughes, 2014; The Environment Agency, 2013; The Environment Agency & English Nature, 2004).

The rivers Test and Itchen, Hampshire, England, are the focus of this study because they are exemplar chalk streams with high groundwater dominance (Base Flow Index 0.94 and 0.91

respectively), clear nutrient-rich water, they feature important habitats such as wetlands, and support high biodiversity (O'Neill & Hughes, 2014; The Environment Agency, 2013). The river Test is used as a representative chalk stream for numerical modelling in Chapter 5. The Test and Itchen River Restoration Strategy (T&IRRS) was developed in response to the findings of River Habitat Surveys which identified major morphological and habitat deterioration compared to national benchmarks for chalk streams (The Environment Agency, 2013). The strategy made recommendations for river restoration, rehabilitation and conservation on a reach scale for the whole length of both rivers (The Environment Agency, 2013). The most common restoration recommendations for the River Test were vegetation management, channel narrowing by in-channel measures by using Large Woody Debris (LWD), partial weir removal or lowering, riparian planting and full weir removal (The Environment Agency, 2013). Additionally, passive river restoration by reducing or ceasing intense river management (weed cutting and dredging) was advocated to improve macroinvertebrate diversity to a higher level than active restoration. Established 'green corridors' (bank vegetation) and in-channel weed growth raises water levels, increases channel-floodplain connectivity, can improve wildlife diversity, and is highly cost effective (Kronvang et al., 2008).

A near-decade of river restoration for biodiversity enhancement has been undertaken, which has focused predominantly on rewilding the main channels. The uptake of the advice has been varied due to many landowners and river managers along the rivers lengths resulting in an array of management practices and river channel shapes, bank material, in-channel vegetation densities, and the presence or absence of large woody debris. This variety in chalk stream channel features represents a variety of requirements from the rivers (i.e., commercial fishing and safe public access), as well as river management preferences. Therefore, chalk stream features and vegetation can be placed on a scale of management intervention with varied influence on channel conveyance.

4.1.1 Flood conveyance and channel hydraulic roughness

Channel conveyance is a quantitative measure of the discharge capacity of watercourse and describes the ability of a river channel to transmit water downslope. As shown in Equation 1, conveyance relates total discharge to a measure of the channel slope where *K* (m/s) is the conveyance, *Q* (m^3/s) is discharge and *S* is the uniform channel gradient.

$$K = \frac{Q}{S^{1/2}} \tag{1}$$

Key to fully understanding the conveyance ability of a river channel is to quantify the channel roughness via the Manning equation. The Manning's *n* coefficient describes flow resistance caused by friction from river channel characteristics. In the Manning equation (Equation 2), *n* is the Manning's roughness coefficient, *Rh* is the hydraulic radius of the river channel, *S* is channel slope and *V* represents water velocity. It can therefore be used to represent different combinations of river channel features on channel conveyance with relative accuracy. Roughness is a widely used parameter to characterise features that alter or influence flows. Additionally, Manning's *n* is an established measure used to approximate channel conditions and NFM interventions in hydraulic models (Dixon et al., 2016).

$$n = \frac{Rh^{1/3}S^{1/2}}{V} \tag{2}$$

Extensive research has been conducted in the past to generate both field-based and theoretical Manning's *n* coefficients for varying coverage and types of in-channel vegetation, bed material, channel shape, riparian vegetation, and the introduction or removal of large woody debris (Dawson & Robinson, 1984; Fisher et al., 2003; German & Sear, 2003; Marshall & Westlake, 1990; Sear et al., 2010; Watson, 1987). The relationship between Manning's *n* values and the impact this has on flow are non-linear. This is because the roughness effects of channel features on flow is also dictated by vegetation structure and shape (Dawson & Robinson, 1984). Channel features also have a seasonal effect on flow conveyance due to fluctuations in water levels and seasonal death and regrowth of vegetation. Watson (1987) observed that conveyance is dictated by the relative height and volume of vegetation relative to stage and discharge, meaning that significant increases in discharge can reduce the relative effect of vegetation and drown out the roughness effect of in-channel vegetation and other channel features (Richards & Hollis, 1980).

Manning's *n* coefficient values for chalk streams are generally cited as ranging between 0.03-0.6 (Clilverd et al., 2016; Goderniaux et al., 2015). The higher roughness coefficients are caused by dense submerged, fine-leaved vegetation, such as Ranunculus, crowfoot and pondweeds which are typical of chalk streams (Fisher et al., 2003). Where this vegetation dominates the channel bed, it can generate enough drag to cause measured Manning's *n* coefficients up to 0.35 (Fisher et al., 2003). This causes a strong seasonal variation in roughness and the conveyance of water in chalk streams where nutrient-rich water and sediment allow for rampant seasonal vegetation growth causing increases in *n* coefficient up to 64-67%, raising the water level (Dawson & Robinson, 1984). This variation in water conveyance due to seasonal vegetation growth has led to the pervasive chalk stream river management practice of bi-annual weed cutting to manage the water levels, usually in early spring and autumn.

Some efforts have already been made to accurately combine multiple river features into a reach-scale aggregated value, such as Cowan's hydraulic roughness estimator and the Conveyance Estimation System (Samuels et al., 2002). The Cowan's hydraulic roughness estimator requires a visual assessment of the features in the river channel, which are allocated an *n* value based on a set criterion and combined into a total value. A study by German & Sear (2003) demonstrates chalk stream measurements of *n* values in chalk streams for restored, modified and semi-natural river reaches vary between 0.0486 and 0.0789. In this instance, river conditions are associated with the related *n* value. In most instances, a roughness range is provided (Clilverd et al., 2016; Hearne & Armitage, 1993; House et al., 2016). However, there does not seem to be a linear relationship between the 'naturalness' of the river reaches and Manning's *n* coefficients (naturalness here being another way for expressing vegetation density). This non-linear relationship is thought to be due to other factors which contribute to roughness, such as channel slope, channel shape, and bed material (Cowan, 1956). Therefore, historical channel planform modifications such as water meadow creation, irrigation channels, widening channels for navigation and dredging will influence present day channel properties such as width, depth and bed material and will play a role in reach-scale Manning's *n* values. Because of this, it is difficult to provide reliable reach-averaged Manning's *n* values for chalk streams with different management approaches and in varying degrees of 'naturalness' and restoration for use in hydraulic models. For this reason, published, unpublished and field-derived (via dilution gauging) Manning's *n* values are collated at a reach scale from a range of sites in this study.

4.2 Methods

A combination of secondary data and field observations were used to derive the variation in chalk stream channel features, the spatial location of these features, and associated Manning's roughness to enable parameterisation of a numerical model. Two chalk river type sites, the River Test and River Itchen were used as the focus of this work. First, the study site is outlined, then management techniques established and linked with channel complexity, prior to attribution of Manning's roughness from published data and field observations.

4.2.1 Study site – The Rivers Test and Itchen

The Rivers Test and Itchen are chalk streams found in Hampshire, Southern England, with a catchment area of 1250 km^2 and 415 km^2 with mean annual discharges of 11.154 m^3/s and 5.894 m^3/s respectively (Figure 14). The majority of both catchments are situated on upper chalk causing a groundwater dominated river regime where the maximum discharge in any given year rarely exceeds 4-5 times the minimum (Acornley & Sear, 1999). Both rivers are intensely modified, particularly in middle reaches due to a network of artificial channels used originally for generating water meadows and for transportation (The Environment Agency, 2013). Today, what is left of the infrastructure is used to manipulate water levels primarily for angling and ecology (The Environment Agency, 2013). Other major human interventions in the rivers include historical dredging, large impounding structures which block the flow of water and routine management of channel and bank vegetation. This kind of management has had major impacts and in 2013 the T&IRRS study found all 8 Sites of Special Scientific Interest (SSSI) on the River Test and all 6 on the River Itchen to be in 'unfavourable ecological status' with the Test considered as the greater concern due to a poorer physical habitat. Since the T&IRRS was published in 2013, management efforts and Environment Agency regulations have been working to reverse this process and restore good ecological status to the SSSI sites as required under the Water Framework Directive legislation. This is achieved by actively encouraging a more 'soft touch' river management style and removing large impounding structures. However, whilst some monitoring efforts have been completed to understand the impacts of these restoration schemes on ecology, none to date have focused on quantifying the impact of river restoration on flood flows and conveyance through the river network.

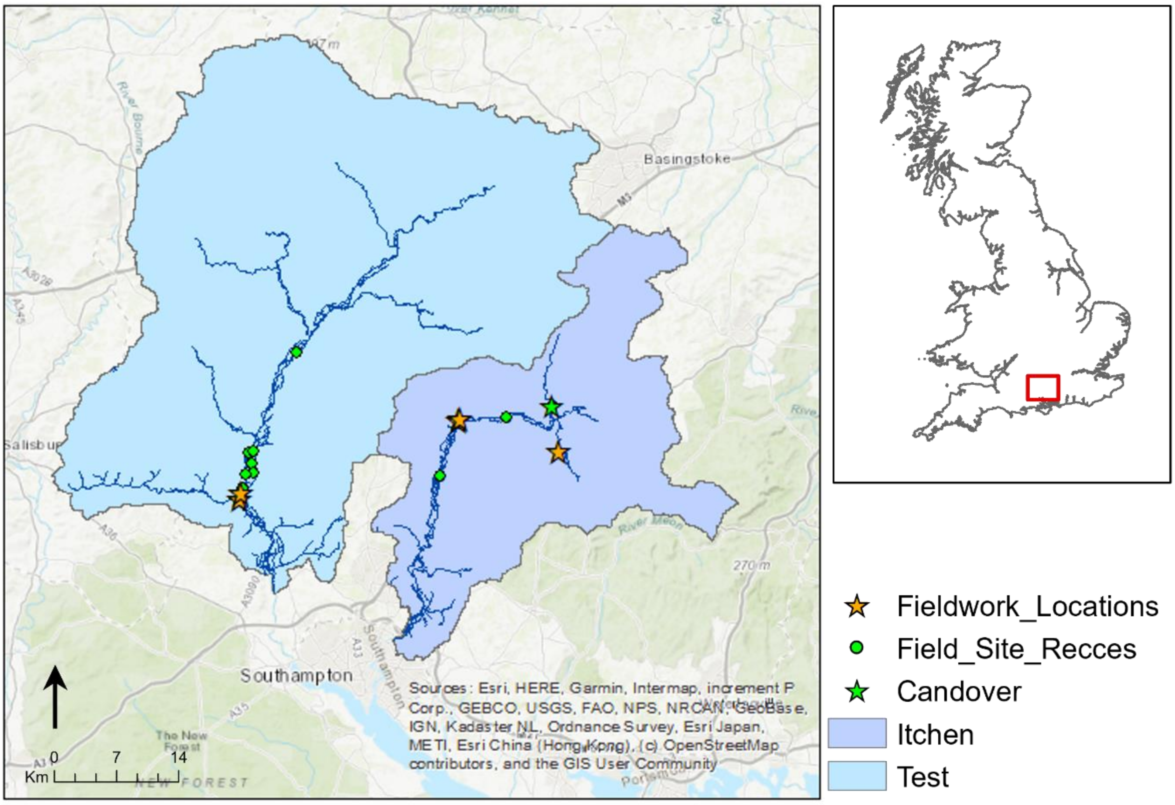


Figure 13 Test and Itchen catchment boundaries showing site recce locations and fieldwork locations.

The River Test has previously caused major flooding in the town of Romsey. Flood events have been recorded in the 1960s, 1995, 2000, 2001, and most notably in the winter of 2013-14. During the 2013/14 event, flooding occurred in 36 residential and 44 commercial properties (The Environment Agency, 2018). Just 6 of these commercial properties incurred estimated losses of £310,000. Including the cost of clean-up, temporary emergency housing, emergency service work, domestic property damage and losses from the rest of the commercial properties, the damages have been estimated in the millions (CH2M, 2014). These floods were caused by prolonged heavy rainfall, with 1015mm of rain in Romsey between Dec 2013 to Feb 2014. Due to the nature of groundwater flooding, the 2013/14 floods occurred during numerous flooding events from December 2013 to February 2014 and some areas were affected repeatedly throughout this time. Road and railway closures caused major disruptions due to being inundated for months. The severity of the 2013/14 flooding led to the design of the Romsey Flood Alleviation Scheme, due for completion in September 2021 (GOV.UK, 2020). The scheme involves modifications to the drainage system, redirecting a side channel and construction of earth embankments.

On the River Itchen, during the 2013/14 flood event, Winchester was prevented from flooding by emergency flood barriers erected by emergency services and the military. Subsequently, the Winchester flood alleviation plan was instituted, as well as a further £1.2 million pledged by the city council to ensure adequate flood protection for the future (Winchester City Council, 2020). During the flood, an experimental measure was implemented upstream of Winchester, in which bags of gravel were dropped into the main channel of the Itchen, to reduce conveyance and force water onto the extensive floodplains before it reached the pinch-point in the city. No effective monitoring was undertaken at the time, so its effectiveness compared to previous flood adaption strategies are unquantified.

4.2.2 Combining river features in to reach-averaged Manning's *n* roughness values

Within the literature there are methods for generating reach-averaged manning's *n* values by combining the sum of river channel features known to influence conveyance. One example of this is Cowan's roughness estimation system (Cowan, 1956). For this method, channel reach roughness is broken down in to six components: 1) basic (bed material), 2) bed irregularity, 3) cross sectional shape, 4) level of channel obstruction (i.e., from large woody debris or engineered structures), 5) vegetation, and 6) the degree of meandering. Cowan (1956) developed a lookup table of Manning's *n* values for each of these channel features, where the combination of these features results in the estimated Manning's *n* for that reach (Table 6).

e.g.,

$$\text{Reach N} = N_1 + N_2 + N_3 + N_4 + N_5 + N_6$$

(Cowan, 1956)

This method has been tested over many years and has been found to be useful for generating general roughness estimates for most streams in the UK (McCuen, 2004). This concept has been built upon for the roughness estimator which is built in to the Conveyance Estimation System (CES) which is a software tool developed in 2002 to improve estimation of flood and drainage water levels in river channels (Samuels et al., 2002).

Table 6 Cowan (1956) computation sheet for generating Mannin’'s Roughness Coefficient from channel reach features.

Variable	Description Alternatives	Recommended value	Actual Value
Basic, n_1	Earth	0.0020	N_1 =
	Rock	0.025	
	Fine gravel	0.024	
	Coarse gravel	0.028	
Irregularity, n_2	Smooth	0.000	N_2 =
	Minor	0.005	
	Moderate	0.010	
	Severe	0.020	
Cross section. N_3	Gradual	0.000	N_3 =
	Occasional	0.005	
	Alternating	0.010-0.015	
Obstructions, n_4	Negligible	0.000	N_4 =
	Minor	0.010-0.015	
	Appreciable	0.020-0.030	
	Severe	0.040-0.060	
Vegetation, n_5	Low	0.005-0.010	N_5 =
	Medium	0.010-0.020-	
	High	0.025-0.050	
	Very high	0.050-0.100	
Meandering, n_6	Minor	0.00	N_6 =
	Appreciable	0.15	
	Severe	0.3	
			Total = Reach n =

The roughness advisor tool within the CES software generates a unit resistance factor for channel reaches by combining roughness values of 3 components: a detailed description of vegetation, bed material and channel irregularities (McCuen, 2004). The features of these three components are assigned a Manning’s roughness coefficient based on pre-set parameters within the software from an extensive literature review. To generate the resistance factor (a unit estimation of roughness), the roughness advisor module finds the squared average of all the components entered by the user

(McGahey & Samuels, 2004). Whilst this is a useful tool, the output roughness range is a resistance factor coefficient, rather than a Manning's roughness coefficient value which is then used for estimating conveyance within the software package and therefore cannot be extracted directly and used as model inputs (McCuen, 2004). The concept of these two methods (i.e., combining features of a river channel to generate a reach-averaged roughness coefficient) was taken and applied. In this case, different parts of the River Test network were assigned to three approximate categories according to channel complexity which is described in the following section.

4.2.3 Mapping the spatial variation in management style

Multiple sites were visited around the Rivers Test and Itchen throughout both catchments (Figure 15). During each visit, the rivers were assessed using a River Habitat- style survey (Appendix 2), using similar classifications regarding the density of the channel and bank vegetation and cross section planform to establish the presence or absence of channel features which are known to influence conveyance (and roughness). Through collaboration with the local Environment Agency and supplemented with relevant literature and reports, the management styles, past river restoration schemes and hydraulically significant channel features on the rivers Test and Itchen were established and river reaches were placed relative to each other on a simplified sliding scale of high medium and low channel management. The River Habitat-style surveys and collaboration with the Environment Agency were used to link specific channel features with these categorisations of channel management. This map and the list of features associated with management styles were used later to approximate Manning's *n* roughness values for input into a hydraulic model (Chapter 5).

The River Habitat-style surveys were used to identify features such as channel shape (width and depth), bank materials, bed material, the presence or absence of vegetation, vegetation coverage, the presence of large woody debris and features that indicate variations in velocity such as pool and riffle sequences and meandering bends. Each feature was given a score according to its contribution to roughness (i.e., boarded riverbanks were given a lower score than wide sedge vegetative river margins). These scores were called river complexity scores and ranged in value from 0, a homogenous low complexity reach to 10, representing a complex, rough reach. A high score could be achieved by multiple features with high roughness contributions and lower scores were associated with a relative absence of features. The complexity scores were used predominantly to categorise river reaches according to the number of channel features to ensure a varied field sample. Complexity scores are linked to high, medium and low management styles in the sense that higher management is associated with greater effort towards channel vegetation removal, practices like dredging and river bed material removal, mown banks and a lack of marginal vegetation and are therefore associated with featureless river channels (Figure 15).

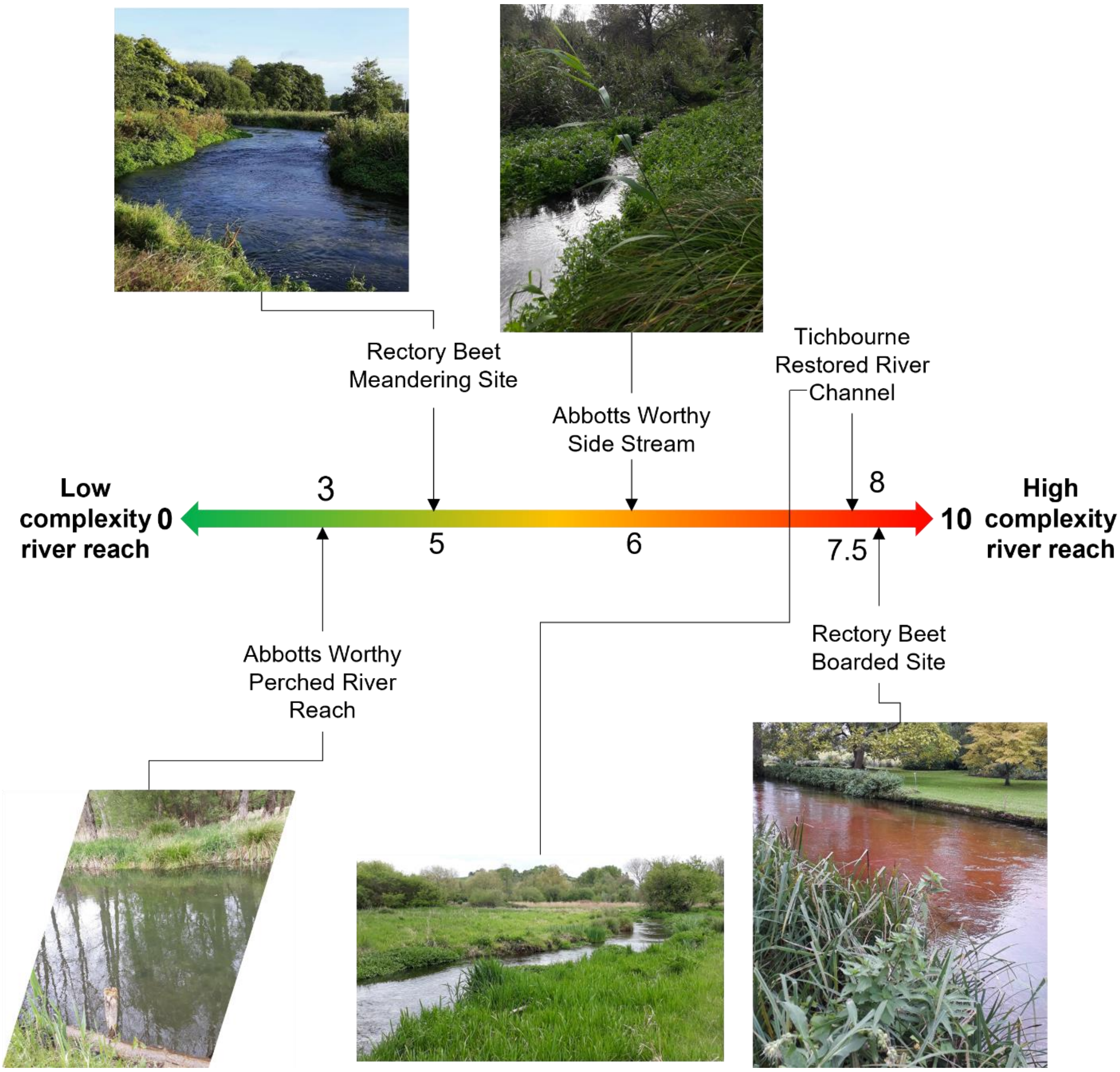


Figure 14 Final field sites organised according to their relative hydraulic complexity. Low complexity (0) is indicative of a lack of bed and bank vegetation, silted riverbeds, and rectangular cross section planforms which are typical of dredged river channels. High complexity river sections (10) are characterised by large quantities of bed and bank vegetation, gavel bed materiel, meandering and other features which generate hydraulic variation throughout the river channel (i.e., woody debris).

Using the complexity scores obtained via the River Habitat-survey style assessments, 4 sites and 6 river reaches were chosen as field work sites for being exemplars of the range of management techniques and channel complexity on the Rivers Test and Itchen (Figure 15). These sites were subject to field-based analysis of roughness using a dilution gauging approach (Section 4.2.4). The 6 river reaches were chosen because they all had physically different features and represent a spectrum of complexity (Figure 15), although ultimately, the final choice of field work sites was restricted by access permissions and the COVID-19 pandemic. As a result, truly 'low complexity' chalk stream river reaches are not represented in the field sample. Figure 16 below is a typical example of a true low complexity featureless chalk stream river reach. This section was estimated to be 20m wide and 3m deep with regular cutting back of sedge river margins and semi-regular dredging, removing bank material and in-channel vegetation. This lack of representation at the lower channel complexity scale was why management style was ultimately used to map channel features and not the complexity scores which were used to categorise river reaches for field work.

Figure 15 An example of a typical low complexity featureless chalk stream river reach which is known to be routinely dredged.

4.2.4 Field measurement of Manning's *n* roughness using the Aggregated Dead Zone Approach

To directly measure Manning's n values for the exemplar reaches, dye dilution gauging was undertaken. Dilution gauging is a method where a known quantity of a fluorescent tracer dye is added in a single injection to a stream of a known discharge to gain a specific dye concentration between 100-500 Parts Per Billion (PPB, the number of units of mass of tracer dye per 1000 million units of total mass). The fluorescent dye is fully mixed in the mixing zone (Figure 16) by a combination of velocity gradients and turbulent velocity fluctuations until the cross-sectional concentration of the tracer dye is nearly uniform. When tracer dyes are mixed into the river channel, dye particles adopt the geometric and dynamic properties of the streamflow (Day, 1976). As the cloud of tracer particles pass the upstream sampling location, they are detected by the fluorimeter. Features of interest are located within the study reach length (Figure 16), meaning changes in hydraulics and channel geometry will influence the flow of water and tracer components through the study reach length, which will lead to changes in the structure of the fluorescent tracer cloud, which are then detected by a fluorimeters at the downstream sampling location (Figure 16). Dead zones are areas in the river channel where flow is retarded, usually caused by a blockage such as vegetation, undulations in the riverbed, and woody debris. Therefore, the aggregate of the effect of multiple dead zones provides an understanding of the retardation of flow caused by features in the river channel. A range of metrics can then be extracted from the results of this analysis, including accurate velocity and streamflow values, river discharge and, importantly for this study, Manning's n roughness coefficient (Carling et al., 2020; Gravelle, 2015).The tracer used in this experiment was Rhodamine WT, which is a red fluorescent dye commonly used in hydraulic analysis of surface water systems (Runkel, 2015). This is because it is environmentally benign and does not cause harm to aquatic wildlife, even in high concentrations (Goodsir et al., 2011; HSBD Toxnet, 2018; Parker, 1973; Rowiński & Chrzanowski, 2011). Additionally Rhodamine WT shows signs of photolysis in natural sunlight in river water (Parker, 1973) and therefore does not persist in an the environment after gauging studies have been carried out. As such, Rhodamine WT is a safe choice of fluorescent dye, both for the user and for the natural environment in which it is used.

Rhodamine Water Tracer dye was added to the river channel in known quantities at a target concentration of roughly 500 PPB or 0.8 mg/L. This target value was chosen because it is far above average background fluorescence levels (between 0.5 – 0.06 µg/L - (Maurice et al., 2006)) and is also

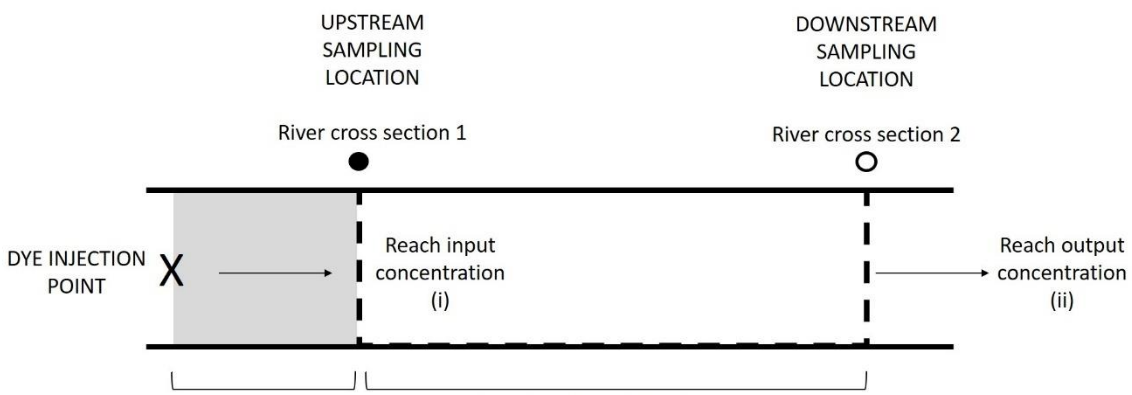


Figure 16 Diagram demonstrating field setup of dilution gauging equipment with an upstream dye injection point, a mixing zone, and the location of the two fluorescence sensors in the river channel.

far below the concentrations used in toxicity tests for Rhodamine WT (between 1 and 10 mg/L - Parker, 1973; Rowiński & Chrzanowski, 2011).

4.2.4.1 Field data collection

To maintain a target Rhodamine WT concentration of approximately 100-500 PPB at each river reach, the dye must be added to the river reach at a quantity relative to the average reach discharge. Channel surveys to establish discharge were completed before analysis to establish the average discharge at each study site before dye injection was calculated using Equation 2 (Fyffe, 2013), where *Qmax* is maximum discharge, *d* is the distance between sensors (Km), *u* is average velocity (m/s) and C_p is the target concentration (PPB).

$$V_I = 3.14 \times 10^{-4} \left(\frac{0.305 {Q_{max}}^{d}}{0.04u} \right)^{0.94} C_p, \tag{2}$$

Each study site was set up according to dilution gauging methods outlined for the Aggregated Dead Zone method (Figure 16 - Carling et al., 2020), with an upstream and downstream detection site. The length of the river reaches varied according to safe points of access to the river channel and the complexity of the river reaches. Each fluorimeter was attached to a Delta T GP1 data logger taking continuous fluorescence readings (PPB) each second. Loggers were set to a standard time, ensuring that the times for both loggers were synchronised.

The injection point was determined mostly by available space and safety, but it was made a minimum of 5m away from sensor 1 to allow for the dye to have mixed adequately across the river channel. Injection was done in a single gulp injection ensuring the dye travels downstream in a single cloud. To reduce the lengths of the mixing zone required for even mixing throughout the river channel, the tracer was spread across the width of the river channel (Barsby, 1967). After each dye injection, the fluorescence was observed at sensor 2 in real time. When fluorescence levels returned to measured background levels it was determined that a repeat injection of dye could be completed. A minimum of three successful tracer injections were completed at each site with final values being the mean of the three successful injections.

4.2.4.2 Post-processing dilution gauging readings to calculate Manning's *n* coefficients for each study site

Using the points from the fluorometer readings at each site, curves were fit to points from the upstream and downstream points using a smoothing spline in the Curve Fitting toolbox in MatLab (Qing-Wan, 2010). Following this, the curves were used to find the timing of events at each reach by finding the time of dye arrival and the time of the dye concentration peak for upstream and downstream sensors (Figure 18). The difference between the peak of the dye (speed=distance/time) was used to calculate the velocity, which was then inputted into the Manning's *n* coefficient equation (Equation 3) to calculate the value of *n* at each reach.

$$n = \frac{depth^{0.666} \times slope^{0.5}}{velocity} \tag{3}$$

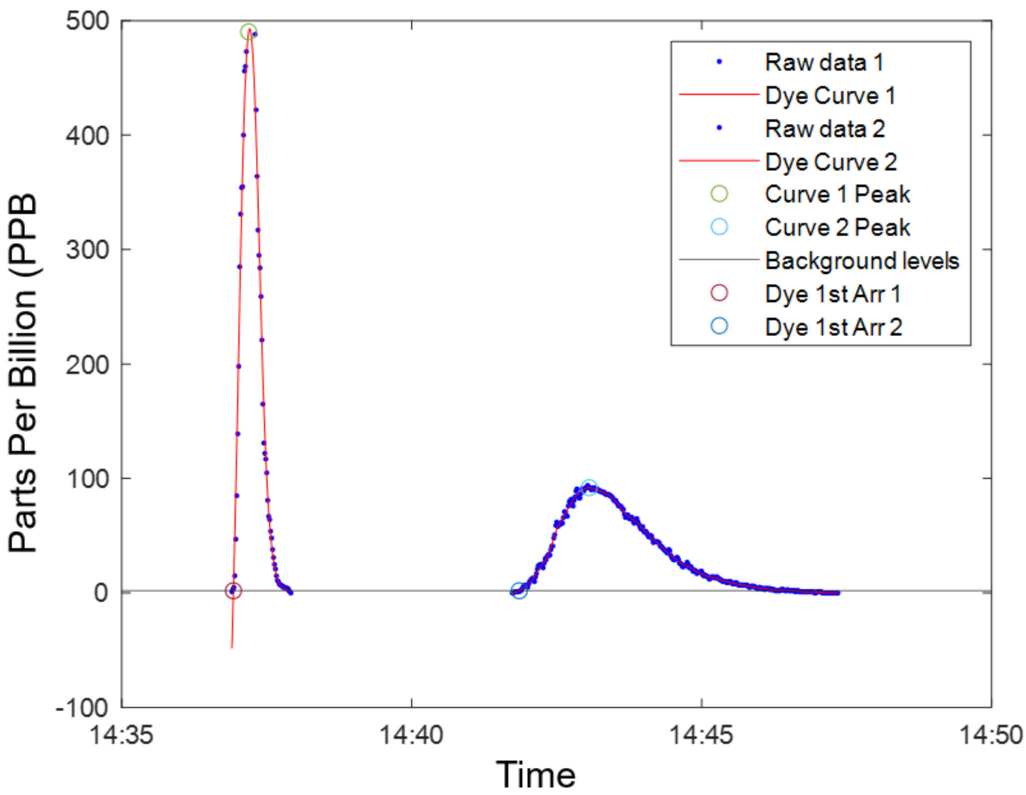


Figure 17 Example of the fitted curves output from the curve fitting tool in MatLab. This is the raw data and fitted curve from the first dilution injection at the Rectory Beet boarded river reach.

4.3 Results and discussion

4.3.1 Mapping of management types and channel complexity

Figure 19 is a map which demonstrates the different management styles and methods across the Rivers Test and Itchen, as well as river restoration schemes implemented across the Rivers Test and Itchen since the river restoration strategy was implemented. This map was developed in collaboration with practitioners from the Environment Agency due to their expertise in previous and planned river restoration works and their knowledge of the current ecological and hydraulic state of the rivers. Practices that are characteristics of each level of management are stated in Table 7, along with the complexity score these features would be assigned during field site visits (Figure 15).

40 structural restoration measures have been implemented across the River Test and Itchen, including 8 structures (weirs) removed, large woody debris implemented in 25 locations, and banks lowered at 4 river reaches. Most of the changes made because of the T&IRRS are managerial, from

heavy management to medium or reduced (natural) management styles. These changes most notably include a cessation in dredging, bank mowing and allowing vegetated margins to grow in and narrow the river channel. This may also include a more conservative seasonal weed cut at the river managers discretion. Currently, the River Test is still more heavily managed than the River Itchen. Additionally, Figure 19 shows the number of different management boundaries. This map represents a conservative estimate of the number of different organisations who manage sections of the Test and Itchen and does not include most of the tributaries. There are at least 29 different management boundaries across both rivers, representing a broad range of management styles. This map is intended to demonstrate that there is variation in management across the many different river sections which results in variable channel features.

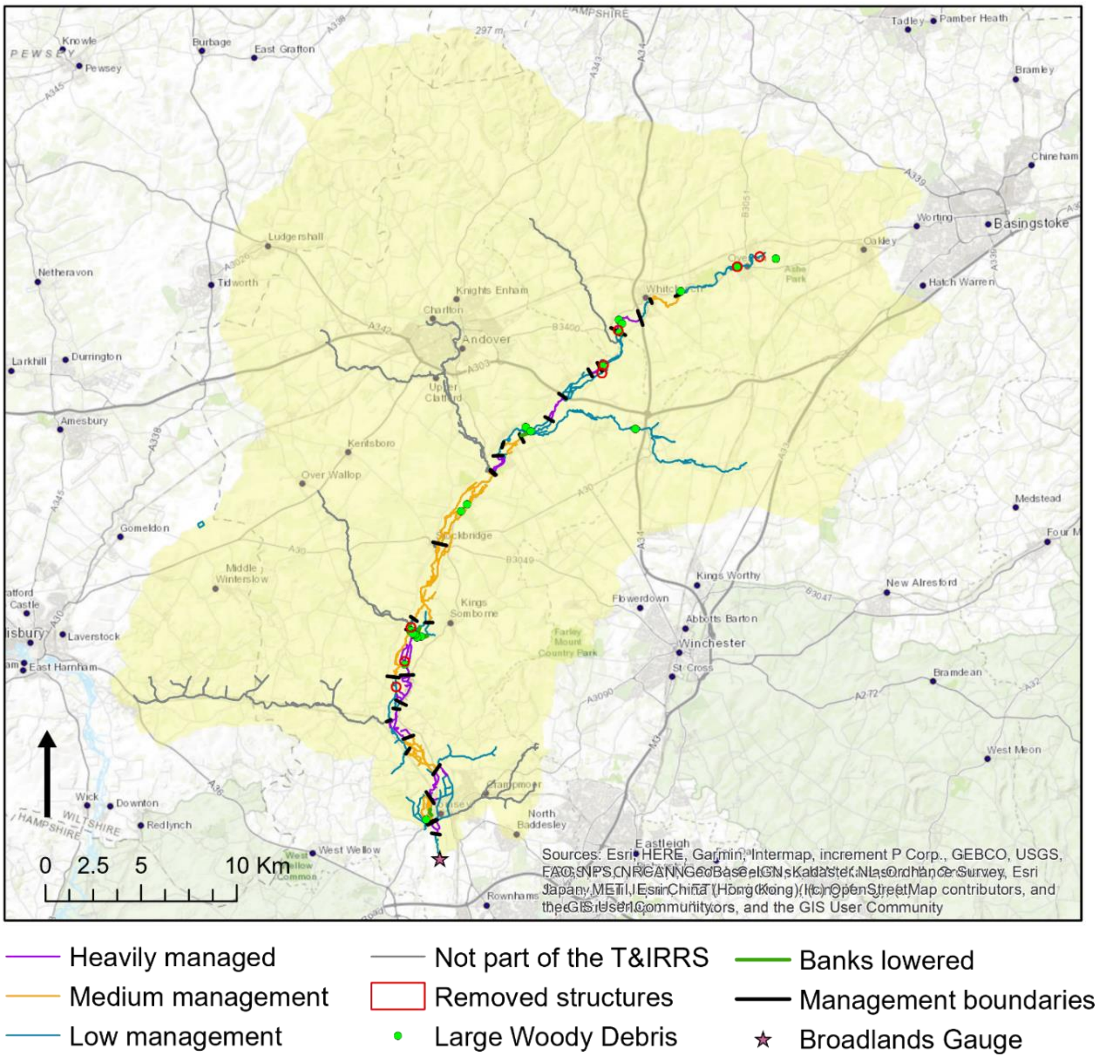


Figure 18 Map showing the different management styles, estate boundaries, and the different restoration efforts on the River Test since the Test and Itchen River Restoration Strategy in 2010. This map was developed in conjunction with local Environment Agency staff who were directly involved in developing the restoration plan.

Table 7 Practices that are characteristic of each management style as categorised in Figure 19 for the Rivers Test and Itchen.

Management style	Characteristics of management style	Complexity score range
Highly managed	• Mown bank margins • Boarded riverbanks • Extensive seasonal weed cuts (unless weeds are required to maintain a suitable water level • Very wide and very deep channels due to the historical and current practice of dredging • Riparian tree cutting to stop wood from falling into the river channel	0-3

Medium Managed	• Bank vegetation is common but often managed (i.e., marginal vegetation = approx. 1m ingress)
	• Seasonal weed cutting
	• Structural restorative changes
	  o Weir removal
	  o Large woody debris implemented
	  o Riparian tree removal or planting wherever necessary
	• Boarded banks and riparian mowing may be present in river reaches with higher public footfall. Other reaches are less heavily maintained
		4-6

Low management	• Bank vegetation is left to grow naturally or with minimum management to maintain responsible public access stewardship • No boarded banks • Minimum possible weed cutting to maintain optimum water levels • Some sections of river channel are restored to natural, or as close to natural morphology as possible. Artificial channels are 'rewilded' where possible. • Generally, large backwatering structures and weirs are removed or are planned to be removed unless they are integral to maintaining viable water levels • Gravel bed material is present or aspired towards • Total cessation of dredging • Biodiversity and flood mitigation are considered in general management.	7-10

4.3.2 Field based estimation of Manning's n for exemplar sites

Field work was conducted at the six field sites selected during autumn and winter 2019-2020. Overbank flooding occurred at the Tichbourne site in January 2020 which was used as an opportunistic field data collection day. Estimated Manning's *n* roughness values are plotted in Figure 20 and summarised in Table 8 along with a description of the river channel at the time of data collection and the associated management style category. Measured field roughness values vary between 0.495 to 0.028 Manning's *n*. The relationship between Manning's *n* roughness scores can mostly be attributed to the presence, absence, and density of bed vegetation in the form of Ranunculus. The sites with the largest quantities of Ranunculus at the time of field data collection generally had the highest Manning's *n* roughness coefficients, despite other channel properties (such as woody deflectors, meanders, and undulating bed levels). This is particularly true of the Rectory Beat Boarded River Reach (Table 8) which, apart from dense beds of Ranunculus at the time of field data collection, had a uniform rectangular channel planform. In terms of channel morphology, bed material and bank material, this was the least varied site. Therefore, despite its relative morphological uniformity, it had one of the highest measured Manning's *n* values. The inverse of this is the Abbott's Worthy side stream (Table 8) which, at the time of data collection, had large quantities of bank vegetation (see Figure 15), predominantly watercress and sedge, woody deflectors had been installed and the morphology included meanders. However, this yielded one of the lowest Manning's *n* roughness scores due to a lack of bed vegetation. There was no Ranunculus as this site and subsequent field visits at an alternative time of year showed that such dense bank vegetation is highly seasonal and that at other times of year this section of river is wide, deep, and has silt bed material.

The Abbott's Worthy perched river reach has an anonymously high measured roughness at a value of 0.495. This is due to backwatering. On the day of field data collection at this site, there were weed cuts occurring upstream of Abbott's Worthy which caused large quantities of cut weeds to float downstream. After field data was collected, it was discovered that a large 'raft' of cut weeds had formed, blocking a large portion of the river channel downstream. Because of this backwatering effect, this measurement was discounted and not used to parameterise hydraulic modelling later. Aside from this, these data do show that Manning's *n* roughness values do vary across the Test and Itchen due to variations in bed and bank vegetation structure and river management.

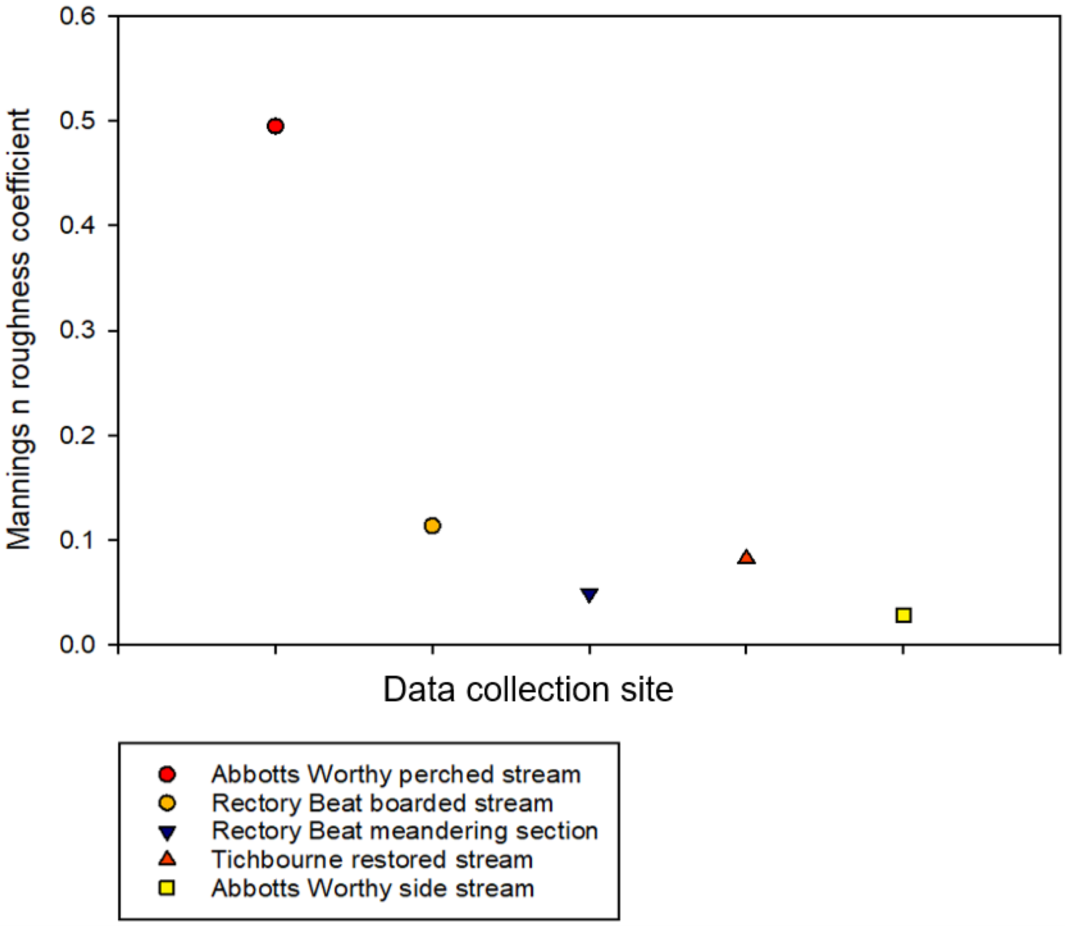


Figure 19 Estimated Manning's n roughness coefficients at field sites on the rivers Test and Itchen using the Aggregated Dead Zone method and dilution gauging.

Table 8 Manning's n roughness coefficients recorded during dilution gauging field work across the Rivers Test and Itchen in winter 2019-2020. Site descriptions are included to provide context of the field site locations at the time of data collection.

Field site	Manning's *n* roughness coefficient	Standard deviation	Site description at the time of data collection
Abbott's Worthy perched river * * results removed due to field work error.	0.495	+/- 0.023	An artificial perched river reach with vertical riverbanks. The river channel has previously been dredged so is relatively deep and rectangular in shape with deep silt as the bed material. There was very little bed vegetation. Bank vegetation consisted of long grass and narrow sedge edges in places (grown in approximately 0.3m). Sections of the riverbank are boarded (for fishing). Field work was conducted during weed cutting upstream which meant there was a large raft of cut Ranunculus weed blocking the channel downstream generating a backwatering effect which affected results.
Rectory Beat boarded reach	0.113	+/- 0.01	A relatively wide and deep section of rectangular river channel with boarded riverbanks. There were large quantities of tall bed vegetation (Ranunculus) covering the majority of the channel bed (estimated 97%) during field data collection leading to a high estimated roughness value.

Rectory beat meandering section	0.049	+/- 0.0001	A wide, shallow, fast-moving river reach with gravel bed material, meanders, and an estimated 40% bed vegetation coverage of short Ranunculus. Marginal bank vegetation consists of a 0.5m sedge edge.
Tichbourne restored river channel	0.082	+/- 0.0009	An upstream reach of the River Itchen. This section has been restored from a straight channel to the original river channel (detected via LIDAR). It is now a meandering river reach with a gravel bed, an estimated 85% bed vegetation (Ranunculus), gravel bed material and vegetated margins (mostly sedge and long grasses) estimated 1m wide on both sides. The channel profile is shallow with sloping banks.
Abbott’s Worthy side stream	0.028	+/- 0.001	A side stream that connects two larger (artificial) channels. It is a deep channel (approximately 1.3m deep) with heavily vegetated riverbanks which constricted the river channel and flow at the time of data collection. Woody deflectors have been installed to narrow the channel and encourage hydraulic variation.

4.3.3 Supplementing field data with theoretical and published data

Roughness values for chalk streams are highly annually variable due to the growth and recession of freshwater plants, meaning that roughness values for chalk streams are presented within the literature as a roughness range. Goderniaux et al. (2015) and House et al. (2016) reported ranges in chalk stream Manning's n roughness of 0.03-0.6 and 0.045-0.353 respectively. These values were used to parameterise hydraulic models and the variation is likely due to accounting for model sensitivity, although both are based on observed data. These roughness ranges encompass the full seasonal oscillation in roughness values caused by annual macrophyte growth. German and Sear (2003) measure roughness values across reaches of the River Wylye, a chalk stream in Wiltshire, that had been modified, restored or were semi-natural. They found that roughness values varied between 0.409-0.0789. Therefore, the roughness range ascertained within this field research (0.028 – 0.495) is within the range of other observations stated within the literature.

Given that flooding in chalk rivers most often occurs during the winter when the water table is highest and macrophyte growth is in the dye-back phase and at its lowest volume. Consistent with this, field work data collection took place from Autumn to late Winter 2019-2020 when weed growth was in the dieback phase. It is therefore suggested that a narrower range of roughness values are relevant to modelling flood events in chalk streams than has been used by Goderniaux et al.(2015) and House et al. (2016) because winter roughness values are most relevant to flood events. Taking this in to account, Clilverd et al. (2016) assigned summer and winter roughness values to approximate this variation. The results from this study, where field work was collected during the winter, represent this narrower range of roughness values.

By noting the presence or absence of channel features, Figure 19 was developed, along with three river management categories (Table 7). Manning's *n* roughness coefficients were assigned to these three categories using the literature and the measured chalk stream roughness values ascertained via dilution gauging. Heavily managed river reaches (associated with the least river channel features) were assigned a value of 0.029 m^3s. This is based on the average of 0.028, the lowest Manning's roughness value measured via field work, and the lowest range of roughness values quoted based on a literature review by other authors 0.03 (Clilverd et al., 2016; German & Sear, 2003; Goderniaux et al., 2015; House et al., 2016). The medium management river reaches were assigned a value of 0.0965. This is based on a combination of the 0.113 measured at the Rectory Beet boarded river section and measured values of chalk stream reaches with study site descriptions that match those qualifying a medium management chalk river reach (Table 7). These features include a channel bed partially covered in trailing vegetation (such as Ranunculus) and dense sedge bank vegetation, generating roughness values from 0.08 – 0.078 (German & Sear, 2003; Watson, 1987). Due to the dense vegetation at the Rectory Beet site, the combined lower value was accepted. Low management river reaches with many hydraulically active features were broken down into two sub-sections: with and without woody deflectors. This is due to the high hydraulic alterations caused by woody deflectors which increase roughness values beyond what is achieved naturally via vegetation growth. During field recces, there was an appreciable (if subjective) difference between areas managed with a lighter touch, and those that had been actively altered and restored with the installation of woody debris for the purpose of channel narrowing and reducing conveyance.

There are multiple values recorded in literature for the hydraulic roughness generated by the introduction of woody debris in the river channel as woody deflectors or other partial channel obstructions varying from 0.08 – 0.32 (Addy & Wilkinson, 2019; Curran & Wohl, 2003; Dixon et al., 2016; Sear et al., 2010; Shields & Gippel, 1993), with most values being stated to be roughly 0.3. However, it must be noted that that the hydraulic roughness of features such as woody debris depend heavily on factors such as the size and shape of the channel and the proportion of the channel that is obstructed by the debris (Shields & Gippel, 1993). Based on the physical description of the woody debris and the degree of obstructions found in the literature, the lower value of 0.083 measured by (Dixon et al., 2016a) was accepted. This is because the woody deflectors implemented in the chalk streams and visited field sites represented a smaller proportion of the channel obstruction compared to others as described in other literature which measured higher values. Woody debris installed in the chalk stream sites were used as woody deflectors with the purpose of narrowing the river channel and encouraging local siltation and river bank encroachment, whereas higher roughness values represented woody debris which spanned and impeded river channel flows. The roughness of large woody deflectors in chalk streams was added to the roughness value for heavily vegetated channels to generate a high roughness value of 0.282.To accurately represent river channel changes on the rivers Test and Itchen, concurrent planform changes that occur due to varying river management also needed to be taken in to account including channel narrowing due to vegetation encroachment and woody debris dams and deflectors and bank lowering to reconnect the channel to the flood plain. In conversations with stake holders, it was found that reduced bank management (especially cessation from mowing banks) often results in a 1m vegetation encroachment on both banks, 2m in total. The final Manning's *n* roughness values associated with differing management styles on the rivers Test and Itchen are summarised below in Table 9. These field-based Manning's *n* roughness values, along with the management style categories and the river channel features that define them (Table 7) will be used directly in Chapter 5 to parameterise roughness values within NFM modelling studies.

Table 9 Roughness values for high, medium, and low complexity river reaches on the River Test as established via dilution gauging and the literature. These were the values used later to parameterise a hydrological model representing a chalk catchment.

Feature	Strickler roughness value	Roughness value (Mannings)	Ingress due to vegetation growth (m)	Justification	References
Heavily managed (non-complex river reach)	34.5	0.029	0	Based on the value measured at Abbott's Worthy Side stream during field work and the lower end of the roughness range established via literature review.	Clilverd et al., 2016; German & Sear, 2003; Goderniaux et al., 2015; House et al., 2016
Medium management	10.4	0.0965	1	Rectory been boarded section field value and medium vegetated channel/sedge edge respectively	(German & Sear, 2003; Watson, 1987)
Low management (complex river channel) – Heavy vegetation only	5.0	0.199	2	Based on a combined value of heavily vegetated chalk stream as measured in the literature.	(Dawson & Robinson, 1984; Fisher et al., 2003; Watson, 1987)
Low management (complex river channel) – with woody deflectors and other hydraulic obstructions	3.5	0.282	2		(Addy & Wilkinson, 2019; Clilverd et al., 2016; Curran & Wohl, 2003; Dixon et al., 2016; Fisher et al., 2003; Sear et al., 2010; Shields & Gippel, 1993)

4.4 Conclusions

In summary, channel management varies widely across the rivers Test and Itchen due to a large number of river managers across both river systems and variable uptake of the recommendations from the Test and Itchen River Restoration Strategy over the previous decade. The restoration strategy advocates for a reduced river management approach, encouraging re-vegetation of chalk streams, which have the capacity to become densely vegetated due to nutrient-rich water and low velocity flows. River reaches on the river Test and Itchen have been mapped spatially according to river management styles. The river channel features that characterise these management styles were established during field site surveys. Values of Manning's *n* roughness were estimated at field sites using a dilution gauging and calculated using the aggregated dead zone method. The results of this analysis show that roughness values do vary according to the presence or absence of river features, particularly the density of trailing channel bed vegetation such as Ranunculus which is a function of weed cutting river management practices. Due to Covid-19 restriction, the number of field data collection sites were limited, and the full range of river management (specifically highly managed, featureless channels) were not well represented in the sample. Field-collected roughness values were therefore validated and combined with roughness values found in the literature to represent the channel features characteristic of each management category more accurately. These categories, their characteristic features, and the map of current management categories on the Rivers Test and Itchen will be used directly to design scenarios and parameterise in-channel NFM model scenarios in Chapter 5.

Chapter 5 Modelling the potential effect of different NFM measures on flooding in the River Test chalk catchment, England, using SHETRAN

5.1 Introduction

Hydraulic modelling studies currently form the majority of the NFM evidence base (Murgatroyd & Dadson, 2019). Hydraulic models are used routinely to test the potential of NFM in target catchments across the globe (Lane, 2017). Modelling studies can be used to test the feasibility of a planned NFM scheme, as well as being able to test multiple combinations of NFM measures, spatial distributions of measures, and area coverage required to generate flood benefits. The alternative is to set up NFM test sites which is demanding for land, financial resources, and time and is often limited by the acquisition of grants and willing participating land owners (Bark et al., 2021; Wells et al., 2020). Even in these cases, hydraulic models are often used as an initial study to narrow down options and to justify implementation (even experimental implementation) to landowners and to gain access to available funding schemes (Forbes et al., 2015; The Environment Agency and CEBEC, 2017). This is the main reason that modelling studies remain the bulk of the evidence base – they are relatively easy to achieve as a stand-alone study, they allow for experimentation at a much larger scale than is practical on the ground, and they are often required as a precursor to NFM implementation.

This chapter follows this pattern. Having established through statistical methods that chalks streams gave variable suitability to NFM due to diversity in hydrogeological pathways and physical catchment characteristics (Chapter 3) and having developed a framework for generating roughness values based on river channel features (Chapter 4), this chapter describes the methods, results, and discussion from a modelling study of NFM implementation in a chalk catchment.

5.1.1 Representing Natural Flood Management in hydraulic models

Modelling studies serve as one of the most fundamental approaches to testing NFM efficacy in any catchment or scenario design. Different numerical models are available which emphasise different physical processes or parts of the hydrological system. One of the greatest strengths of numerical modelling is the customisation available through altering model parameters and data inputs. Due to the range of features within the category of NFM and the different hydraulic processes they influence, many different approaches can be taken to represent NFM in numerical models (Dadson et al., 2017). For this reason, a short summary of the methods used previously to represent NFM in modelling studies is provided. This is intended to place the methods used in this study within the context of the established modelling methods. Each NFM measure has a description of the methods as found in the literature, followed by a short summary at the bottom of each section.

5.1.1.1 Leaky barriers

A review of the modelling literature regarding leaky barriers found that the majority of studies altered flow resistance and/or roughness values within the river channel to represent the reduction in velocity and conveyance caused by partial blockages in the river channel by leaky barriers (Adams et al., 2019; Anderson et al., 2006; Dixon et al., 2016; Ghavasieh et al., 2006). Other studies took a different approach by representing 3D structures within the river channel taking advantage of the St Ventant's equation in 1D models to represent the restriction of flow through gaps. This approach modifies the stage-discharge relationship for areas where leaky barriers are located. Here, they were represented as a weir or hydraulic jump, with associated energy loss, hydraulic jump, and return to subcritical flow contained within a sub-reach (Metcalfe et al., 2017; Rana et al., 2017). Thomas & Nisbet (2012) took a combined approach, modelling both partial obstructions within the 1D river channel module of the model and altering the generalised Manning's roughness values of the river channel parameters. Samra (2017) represented leaky barriers via a porosity coefficient, representing the gaps between the sticks and leaves that allow water to escape past the woody debris. This was defined as the total channel area of voids between woody debris mesh divided by the total dam area.

Addy & Wilkinson (2019) provide a summary of the ways in which Large Woody Debris dams (LWDs) in river channels (a type of leaky barrier) are represented within hydraulic models. In their literature review of 31 LWD modelling studies, they found that the majority of authors chose to represent LWD by increasing reach-scale channel roughness parameters (9 of the studies used this approach). Within their summary Addy & Wilkinson (2019) identified six other methods of representing leaky barriers in hydraulic models including: altering channel geometry (7), geometry and channel roughness adjustments (5), representing hydraulic structures such as weirs or constricted flows (6), roughness and hydraulic equation adjustment (1), explicit 3D representation (2), and a porosity model (1).

Summary

Based on these findings, it can be concluded that most modellers choose to represent leaky barriers as increases in roughness values or representing channel obstructions which constrict simulated flows or alter stage-discharge relationships.

5.1.1.2 Woodland

Within the literature, there are two distinct types of woodland creation for natural flood management: 1) floodplain or riparian woodland located proximal to the river channel, or 2) catchment woodland. Overwhelmingly, floodplain and riparian woodland are represented by altering roughness values for the wooded area next to the river channel (Anderson et al., 2006; Dixon et al., 2016; Ghavasieh et al., 2006; Nisbet et al., 2015; Samra, 2017) or as increased turbulent flows caused by the effective area of tree trunks disturbing overland flow pathways (O Connell, 2008). Catchment woodland is represented as a function of the storage, interception, and soil porosity and infiltration capacity of soils, with these relationships represented in slightly different ways in different studies (Hankin et al., 2019; Jackson et al., 2008; Rutter et al., 1971; Salazar et al., 2012).

Rutter et al. (1971) modelled the hydrological effect of increasing the area of pine woodland in a catchment as overall interception loss. The model represents the storage of water in the canopy to calculate net rainfall (the rainfall that reaches the ground surface). The store is added to by intercepted rainfall by leaf area index and depleted by evaporation and drainage. Due to evaporation and drainage rates varying over time due to the wetness of the canopy, the model calculates the running balance of water storage as the sum of gains minus losses, with evaporation from the wetted canopy representing the interception loss. On the other hand, Salazar et al. (2012) focused on the soil altering effects of increasing woodland area. In this study, an increase in the wooded area in a catchment was represented as an increase in upper soil capillary capacity (values obtained via the literature) and therefore soil storage capacity. The predicted area of the leaf canopy was also used to estimate the amount of rainfall intercepted by the leaves and plants before falling on the ground. Hankin et al. (2019) and Jackson et al., (2008) took a combined approach. The Leaf Area Index was used to calculate estimated net rainfall (the amount of rainfall that reaches the ground surface beneath the tree canopy) as a balance between rainfall and wet canopy evaporation. Infiltration rates were modified in woodland areas to represent the increase in capillary flows following the root structure in to the soils, and roughness values represented the hydraulic roughness caused by the exposed tree trunk and root networks (Hankin et al., 2019; Jackson et al., 2008).

Summary

Within NFM models, there are two different types of woodland creation: woodland represented proximal to the river channel and catchment woodland. Woodland proximal to the river channel is normally represented as alterations to the roughness parameters in the wooded area. Catchment woodland is represented as a function of the storage, interception, and the soil porosity and infiltration capacity of soils. There is a slight variation in the emphasis and detail of the simulated hydrological processes of the trees between studies and models.

5.1.1.3 Storage ponds

The main approach to modelling storage ponds is editing the catchment elevation model to generate topographic low points and/or raised sections of land (bunds) (Callow & Smettem, 2009; Hankin et al., 2019; Metcalfe et al., 2017; Samra, 2017). Because of the flow routing equations within models, the water is simulated as trapped within the dips or trapped behind the bunds and doesn't reach the river channel as quickly. Through a comparison of field studies and this modelling approach, (Callow & Smettem, 2009) were able to show that changing catchment topography within models is an accurate representation of the hydrological effect increasing catchment storage in this way.

The other main method is to calculate the volume of water that could potentially be added to a catchment via storage ponds is through prescribing a catchment attenuation storage coefficient. This volume of storage can then be artificially removed from the simulated runoff. In this method, the volume of storage for each scenario is selected (or calculated) beforehand, and a linear attenuation storage-discharge relationship calculated based on this volume. The attenuation effect of storage ponds is therefore represented as the relationship between storage and discharge from ponds as a proportion of runoff within the catchment (Adams et al., 2018; Salazar et al., 2012).

Summary

Storage ponds are most often represented within models by editing the catchment elevation data, which is fed in to the 2D model, manually lowering the elevation to form dips for ponds, or raised bunds that trap runoff behind them. This method has been compared to field studies and has been found to represent the key hydrological processes of storage ponds well. The other method is to approximate water storage volume that could be added to the catchment by creating storage ponds and deducting this volume of water from simulated runoff.

5.1.1.4 Buffer strips, tree shelter belts, and hedgerows

A lot of hedgerow, buffer strip, and shelter belt modelling studies focus predominantly on the sediment trapping potential of these features (Lerch et al., 2017; Mullan et al., 2016; Nieswand et al., 1990). This demonstrates that their perceived main benefit is their ability to capture sediment and improve water quality by intercepting surface runoff, rather than the explicit flood reduction benefit that this runoff interception could cause. Where buffer strips are modelled for their flood peak reduction potential, they have been represented as sections of land with increased Manning's roughness values relative to their surrounding land area, simulating a reduction in runoff conveyance and velocity (Nieswand et al., 1990). Samra (2017) represented hedgerows as porous physical obstructions in the landscape. Similar to the way they represented leaky barriers in the river channel, the area of the hedge is divided by the area of the voids between woody sections of the hedge to calculate flow area. Lerch et al. (2017) and Mullan et al. (2016) chose to represent buffer strips via land cover classifications. Vegetated buffer strips were classed within the model as grassland or low vegetation with the surround areas classed as arable land. The root depth and capillary flow properties of these land cover classes simulated the infiltration properties of the buffer strips, as well as the evapotranspiration properties of the vegetation types. Manning's roughness values were also parameterised for different vegetation types.

Summary

In the literature and modelling studies about buffer strips, tree shelter belts, and hedgerows, the focus is predominantly on their sediment trapping capability as opposed to their flood reduction potential. It is inferred from this that sediment trapping is their main practical application, rather than flood management. However, because sediment is trapped, it can be inferred that overland flows are intercepted and slowed but few studies have quantified this effect. Shelter belts are represented in models as Manning's roughness values, porous blockages within the landscape, and as vegetative land cover types. Where land cover is specified, soil infiltration rates and evapotranspiration processes are often represented.

5.1.1.5 Wetlands and washlands

Modelling the effect of wetland and washlands (designated flood areas adjacent to the river channel) is done within models which are capable of representing groundwater-surface water interactions because this is one of the key processes in wetland areas (Clilverd et al., 2016; House et al., 2016). In these cases, the horizontal and vertical hydraulic conductivity values are represented within the saturated zone of the underlying bedrock. In both studies, the exact parameters for the permeability, transmissivity and hydraulic conductivity of the sub-surface geology were ascertained through field work, hydrogeological data, and refined during model calibration. Clilverd et al. (2016) took a simplified approach and represented floodplain sub-surface dynamics as a simple one-layer saturated zone representing the average geological condition in the upper alluvial and glacial soils found at the site. House et al. 2016) represented sub-surface processes as a stack of multiple layers with different hydraulic properties. The unsaturated zone was represented as a spatially uniform profile of peat soils at a 1m depth, with Van Genuchten, soil moisture retention curve, infiltration rate, and effective saturation were parameterised through a combination of literature and calibration. The saturated zone was characterised as a four-layer geological model with peat overlaying gravel over a discontinuous layer of (impermeable) putty chalk and chalk bedrock beneath. The spatial location and depth of to each layer was obtained via field surveys. The 3D finite-difference Darcey flow method was applied to calculate the rate of subsurface flow and the exchange between the aquifer and the river channel were parametrised to be controlled by the hydraulic conductivity to allow for exchange between the river channel and the aquifer. This allowed for the processes of groundwater and surface water interaction to be successfully represented for this study area after calibration.

Summary

One of the key hydrological processes of wetlands and washlands is groundwater-surface water exchange. Therefore, models used to represent these landscape features must be a good proxy for these processes. Both vertical and horizontal movement of water are represented, with the rate of this movement usually parameterised via field-collected values and refined during the calibration processes. The hydraulic properties of sub-surface flows are represented as a simplified lumped value or as a highly detailed stack with multiple layers with different hydraulic properties as a more realistic representation of subsurface geology.

5.1.1.6 Key limitations of modelling NFM

Whilst models are highly useful tools to test the possible catchment response to NFM implementation, there are some inherent limitations for using models as evidence for NFM. Our understanding of hydrological processes, including those associated with flooding, is incomplete and therefore there are uncertainties in how to represent these in models (Beven, 2012). This is particularly true in the case of modelling ungauged catchments and can lead to inaccurate flow and flood estimates. Furthermore, there are often uncertainties associated with model parameterisation because complex physical processes are simplified as model parameters (Lane, 2017). As a result, inaccurate hydrological estimates and uncertainties from model parameterisation can compound (Hankin et al., 2017). Wide uncertainty margins can make it difficult to detect changes caused by the implementation of NFM within the model and make it difficult to apply practically the results from modelling studies. Therefore, models are helpful tools to experiment with different NFM measures before implementation. However, observational studies and observed data are always optimal for evidence compared to modelling studies by removing some of the uncertainty and simplifications which are associated with modelling.

5.1.2 Chapter outline

As summarised above, there are many ways to represent various NFM interventions in numerical models. Modelling studies are a relatively simple, cheap, and low risk way to test the potential and suitability of NFM schemes and their spatial orientation within a target catchment and are often used to justify planned schemes or to guide NFM design. A large proportion of the current evidence base is grounded in modelling studies. At the time of writing, there is very little research testing the effectiveness for NFM as a flood mitigation strategy specifically in groundwater-dominated chalk catchments. This chapter is intended as an initial investigation into this using the SHETRAN model to represent the complex groundwater-surface water interactions in chalk catchments, as well as channel and land cover NFM interventions. The NFM interventions chosen for modelling (increasing the land cover area of deciduous woodland and in-channel revegetation and large woody debris installation) were based on the results of the statistical analysis in Chapter 3. Field work-based roughness values from Chapter 4 were used to parameterise the river channel for in-channel NFM scenarios. This chapter outlines the approach to model setup and scenario design. As one of the first studies directly modelling the effect of NFM in groundwater dominated catchments, the findings are put in the context of other modelling studies assessing similar NFM interventions in other catchment types. The implications of the findings are then discussed.

5.2 Methods

This section outlines the process of setting up and executing an NFM modelling study on the River Test, a chalk stream in the Southeast of England. First, a justification for using the SHETRAN model in the chalk stream environment is presented, along with details on the main processes represented within the model, input data and basic parameterisation. The metrics used to measure flooding in this study (i.e., flood peaks, flood duration, the number of floods and total time flooding) require a flood threshold. This was obtained via a rating curve which was developed using stage and discharge data from gauges around the Test catchment. Following this, model calibration was tested through visual inspection of observed and simulated data and the Nash-Sutcliffe Efficiency coefficient. After establishing that the model is adequately calibrated, a short sensitivity analysis was conducted to ensure that the SHETRAN model is sensitive to changes in deciduous woodland cover and alterations to the channel roughness values within the range that was established in Chapter 4. The methods used to generate scenarios are then outlined, along with scenario designs. In-channel NFM scenarios are based on the recommendations from the Test and Itchen River Restoration Strategy, and woodland creation scenarios are based on woodland opportunity mapping by Forest Research. Care was taken to ensure that scenarios are representative of realistic (or previously recommended) changes on the River Test, to give a more realistic understanding of the potential for NFM in chalk catchments.

5.2.1 The SHETRAN model

The model used to assess the potential impact of NFM in the Test catchment is SHETRAN, a physically based, spatially distributed model based in the Système Hydrologique Europeén (SHE) which was originally developed jointly by the British Institute of Hydrology, the Danish Hydrological Institute and the French company SOGREAH (Abbott et al., 1986; Bathurst, 1986). The SHE model was later adapted by Newcastle University by building on the mathematical and physical descriptions of flow processes by Freeze & Harlan (1969) to include sediment and solute transport (SHETRAN stands for SHE-TRANsport -Bathurst & Purnama, 1990). As a result, SHETRAN is a three-dimensional coupled surface/subsurface difference model for coupled water flow, multi-fraction sediment transport and other reactive solutes transfer in river basins (Ewen et al., 2000; Lewis et al., 2018).

The main strength of SHETRAN in the context of modelling NFM in groundwater-dominated catchments is its comprehensive representation of groundwater and groundwater-surface water interactions. This allows it to represent the interactions between groundwater levels, streamflow, and resultant flood flows. Subsurface three-dimensional flows can be modelled for a combination of confined, unconfined, and perched aquifer systems. Variations in saturation and porosity of the bedrock medium are included in the model (Lewis et al., 2018). Importantly, the unsaturated zone is included as a part of sub-surface flow and is coupled directly with surface flows. This linkage of surface and subsurface processes along with the detail of groundwater modelling allows for comprehensive surface and groundwater modelling to occur simultaneously in the same model (Ewen et al., 2000). It is therefore possible to make reasonable adjustments to the model parameters and input files to represent NFM interventions, whilst maintaining the capability of modelling groundwater/surface water interactions in sufficient detail to represent a permeable chalk catchment.

5.2.1.1 Representation of surface and groundwater processes in SHETRAN

SHETRAN is designed to simulate flow processes at the catchment scale. In general terms, SHETRAN uses meteorological inputs to drive the water balance at the land surface, with a channel network fed by surface and subsurface responses to rainfall and measured at user defined outflow points (often an existing flow gauge). SHETRAN represents the catchment as an ensemble of columns (Figure 21). This allows SHETRAN to represent three dimensional flows, with water transferring vertically from the surface to the subsurface (and vice versa) and horizontally. Columns are typically made up of more than one layer of varying porosity and hydrogeological properties to represent variable geological features in the saturated and unsaturated sub-surface (House et al., 2016). These flows are calculated based on meteorological inputs (precipitation and snow), measured or calculated potential evapotranspiration and heat budgets (used for calculating snow melt). Net precipitation to the ground is measures as incoming precipitation minus interception, evaporation, and vegetation drainage. Potential evapotranspiration (PET) is calculated within the model as a dynamic function of input PET values and soil moisture conditions in each timestep. Infiltration into the ground is simulated from net precipitation to the ground and calculated surface water runoff. The spatial distribution of soil moisture within the model is simulated, with accompanying pressure in the unsaturated zone and recharge to the saturated zone of the aquifer. Transmission through the saturated zone is calculated as a spatially variable, anisotropic unconfined aquifer. Exchange flows between the aquifer and the river channel are assumed and computed regardless of known channel bed material and lining. Therefore, SHETRAN can represent sources and sinks of channel flows via aquifer exchanges through the channel bed and banks.

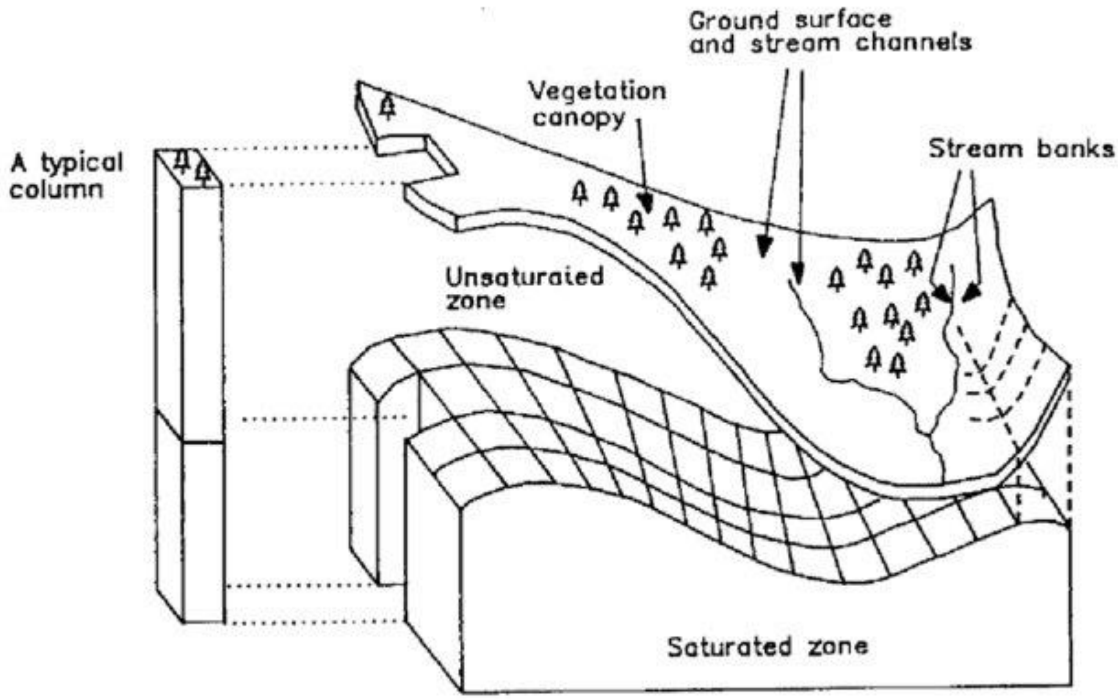


Figure 20 The structure of the SHETRAN model grid representing hydrological catchment processes. Each grid square is a column with multiple layers representing spatially variable hydrogeological processes. The number of layers and layer properties can be defined by the user for each grid square. From Shrestha (2013).

Surface water is generated as infiltration excess or saturation excess flows. A river network is used for channel routing through the catchment. Channels are represented as reaches of specified size defined by cross-sections at the resolution of the catchment grid. Overland flow is directed to the river channel as sheet overland flow and backwatering and overbank flows can be represented at the same grid scale as the catchment. Grid squares (and therefore channel network reaches) have to accommodate the whole catchment and computation time.

It has a modular design, with each different module calculating a different part of the hydrological function of the catchment. The modules of SHETRAN are the frame module (used to control the simulation, including initialisation timestep, result output and termination), the water flow component, the sediment transport module, and the contaminant transport (Birkinshaw, 2011). Contaminant and sediment transport are not the focus of this study, and therefore these capabilities of SHETRAN were not used. The water component further breaks down in to four more modules: the evapotranspiration/interception module, the overland/channel module, the variable saturated subsurface module, and the snowmelt module (the latter was not included).

The frame module is used to dictate the model setup including the grid element size (spatial resolution of the model) and making sure all data is called in the correctly. The frame module also sets out the spatial construction of the catchment in SHETRAN by setting up the numbers for each catchment element. The catchment area is made up of grid elements. Each grid element is a column with vegetation, the ground surface, soil depth and then subsurface properties. Channel link elements are run along the edge of grid elements and make up the simulated river network. Each channel link can be assigned with individual cross sections if required. The time step is also defined in the frame module by the user and the variation in the timestep is calculated by SHETRAN in this module.

The evapotranspiration module calculates evapotranspiration in the catchment for each grid cell and translates this to a loss term that is then used to calculate soil moisture and subsequent infiltration and aquifer recharge rates. Evapotranspiration calculations include losses from plant transpiration, plant uptake from the soil in the root zone, canopy storage, drainage from the canopy, precipitation beneath the canopy and evaporation from the wetted canopy, bare soil (including dry channels) and from free water surfaces. Potential evapotranspiration (PET) can be calculated directly within SHETRAN via the Penman-Monteith equation from meteorological data or can be inputted as a PET time series (Birkinshaw, 2011). The Penman-Monteith equation assumes an unlimited supply of water to a dry canopy and that the only limitations to evapotranspiration are the meteorological conditions and the surface area and aerodynamic properties of the vegetation. Therefore, PET is used as the upper limit of actual evapotranspiration for each grid element in the catchment at each time step. Actual evapotranspiration (which is applied as a loss term to infiltration and aquifer recharge) in the model accounts for resistance for water movement through vegetation by applying a canopy resistance factor based on stomatal vapour flux (Monteith, 1965) to each vegetation type. The evapotranspiration module assumes that transpiration occurs at the actual rate from the total leaf area. When the canopy is at maximum capacity (totally wetted), intercepted water is represented as evaporating at the actual rate and transpiration is zero. Evaporation from bare soil is only calculated for areas of bare soil not covered by vegetation (from a theoretical aerial view). Therefore, evaporation on areas of bare soil is assumed to occur at the actual rate, weighted against the proportion of ground not covered by vegetation. Rainfall interception in SHETRAN is the net precipitation that reaches the ground through the vegetative canopy. SHETRAN uses a basic balance equation which calculates interception as the ratio of leaf area to the total ground area. This uses an equation by (Rutter et al., 1971, 1975) and applies it to all vegetation types because the physical principals are the same, despite being originally designed to represent trees. This equation considers the canopy to have a finite capacity which is filled by rainfall and emptied by evaporation and drainage. The canopy surfaces are considered fully ‘wetted’ when this capacity is reached. The surface area of the vegetation (both leaves and branches) varies seasonally meaning that so does the evaporation and interception potential. When the depth of water falling on the vegetation canopy exceeds the calculated canopy storage, evaporation from the canopy is assumed to occur at the potential rate (i.e., the maximum possible). When storage capacity in the canopy exceeds rainfall, it is represented as PET multiplied by the ratio of intercepted rainfall divided by the storage capacity. Therefore, the evapotranspiration module in SHETRAN calculates evaporation from intercepted canopy storage, then calculates the net precipitation as precipitation which falls directly to the ground plus drainage from the vegetation canopy (weighted for the proportion of ground not covered by vegetation), then calculates soil loss from the root zone using vegetation properties (giving the loss term for infiltration) resulting in an overall calculation of evapotranspiration for each grid cell in the modelled catchment.

The overland channel flow module calculates the surface water on the ground in catchment grid elements and in channel link elements, as well as flows between elements. SHETRAN uses diffusive wave approximations of the full suite of St. Venant equations meaning it is capable of simulating backwatering effects (at the scale of channel link and grid spatial resolution). Flows can occur between any SHETRAN element type (gird, channel link or bank element) and occur as Manning’s resistance flow equations between two grid elements or into the channel link elements, or are represented as flows through a flat crested weir for bank overtopping. Smaller cell sizes allow these transfers to be represented in greater detail. Boundary conditions are set as a no-flow boundary at the catchment boundary as a default, but head boundary data can be prescribed manually for any grid, bank or link element. Flow boundary data are given as a function of time at the catchment boundary only and are assumed to enter through the catchment through one arbitrary face of the grid element. Channel links have prescribed flux flows, with all boundary data for the channel given at the downstream end of each channel link. Channel links can also represent flat crested weirs (along with a weir adjacent to the river channel) by the user. Downstream outflow is either represented as prescribed flux flows or as a flat crested weir in cases where gauging station dimensions are known.

The variably saturated subsurface module calculates all subsurface flows in SHETRAN. The model simulates fully three-dimensional flow in the saturated and non-saturated zones in assumed anisotropic and spatially variables media. Flow is simulated through multiple layers of porous media of differing characteristics, modelling upper and lower soil horizons and bedrock below as a column for each grid element. Because multiple layers can be specified, confined, semi confined and unconfined aquifers as well as perched aquifers can be simulated. A lower boundary (either a gaining or loss boundary) and edge boundary conditions can be specified by the user, but a no flow boundary is the default in both cases. Upper boundary conditions (i.e., representing infiltration) are represented as a prescribed time-varying head where surface water is present and as a mixed type boundary condition when no surface water is present. This mixed type boundary condition scenario is the balance between precipitation inputs and evapotranspiration outputs (the loss term calculated in the evapotranspiration module). SHETRAN automatically switches between these two boundary conditions as is appropriate. The relationship between volumetric soil water content and pore water pressure is described by a water retention curve calculated within the model from soil moisture characteristics which are usually derived from the soil characteristics found in mapped input data. Three-dimensional sub-surface flows are calculated as a function of hydrostatic pore water pressure over time considering storage capacity and infiltration based on the water retention curve. Stream-aquifer interactions are represented by two processes: 1) flow through the channel sides is based on a time varying pressure gradient causing water to move in or out of the channel depending on the direction of the gradient and 2) flows through the channel bed are represented the same as any other vertical transfer throughout the model dictated by the permeability of prescribed channel bed material. Additional sub-surface processes such as groundwater abstractions and spring flows can also be represented in SHETRAN.

In summary, SHETRAN uses a modular model structure to calculate multiple different hydrological catchment processes, including rainfall, evapotranspiration (including canopy storage and interception), overland and channel flows with associated backwatering effects and sub surface flows. In its most basic forms, SHETRAN models overland-channel flows and basic groundwater-surface interactions measuring outputs as flows at the lower boundary of a downstream channel link. Additional modules and processes can be simulated in SHETRAN at the users discretion.

5.2.1.2 Input data

Lewis et al. (2018) developed an automated setup of the SHETRAN model for the whole of Great Britain. They were therefore able to provide a baseline parameterisation of SHETRAN for the Test catchment along with all the required data inputs. This significantly reduced the setup time for modelling the Test catchment and provided a safe launch pad from which to optimise parameterisation and to experiment with the capability of SHETRAN to represent NFM. The SHETRAN model at a minimum requires: a Digital Elevation Model (DEM), a land cover map, a rainfall time series, a Potential Evapotranspiration (PET) time series (or meteorological data which can be used to calculate PET within the model), and a mask which defines the catchment area. For this study a soil cover map was also used to define the variable sub-surface module parameters. Having used an automated setup version of the Test catchment provided by Lewis et al. (2018), the majority of the input datasets are the original data as stated and justified in their journal article. To extend the model run time beyond that provided by Lewis et al. (2018), alternative rainfall and PET time series were sourced according to data availability. Using these alternative rainfall and PET datasets allowed the model duration to be extended to a period between 1990 to 2017, increasing the number of floods within the model outputs to improve flood estimates.

Precipitation was derived from the CEH-GEAR daily gridded estimates (Tanguy et al., 2019), which is a 1km gridded rainfall database derived for the UK from 1890 to 2017. The gridded data are derived from the Met Office national database of observed gauge precipitation by using the nearest neighbour interpolation method with a data normalisation applied. Estimated daily rainfall refers to estimated precipitation for the 24-hour period (mm/day) from 9am to 9am to the following morning. For input into the SHETRAN model, the CEH-GEAR dataset was cropped to the catchment area. The Potential Evapotranspiration (PET) dataset used was the CHESS-PE dataset (Robinson et al., 2020). This is a 1 km gridded PET (Kg/m^2) estimate for Great Britain from 1961-2017 derived using the Penman-Monteith equation assuming a well-watered grass surface. The meteorological variables used to calculate PET are derived from a combination of the MORECS Met Office 40km gridded dataset (Hough & Jones, 1997; Thompson et al., 1981), the CRU TS 3.21 (Harris et al., 2014), and the WATCH Forcing Data datasets (Weedon et al., 2011). Rainfall inputs are based on the previous version of the CEH GEAR dataset (which adds the benefits of consistency across datasets) (Keller et al., 2015), adjusted for the use with the JULES method. The CHESS PE dataset is calculated following the Food and Agriculture Organisation of the United Nations (FAO) standards for computing PET (Allen et al., 1998) which provides PET estimations for 1km grid squares across England per day (mm/day) based on measured meteorological data. As part of this dataset, PET with interception correction is also available, but this was not used considering that this process is calculated within the SHETRAN model internally. Both these datasets are open source, are widely used and are generally accepted to be high quality data. The relevant 1 km grid squares for the River Test catchment were extracted using the dimensions of the SHETRAN input data as provided by Lewis et al. (2018) and then reformatted as required.

The full details of how the source datasets and derived data inputs were chosen for the automated setup of SHETRAN for Great Britain can be found in Lewis et al. (2018) but is summarised below. The DEMs, derived from the 50m Ordnance Survey Land-Form Panorama data (Ordnance Survey, 2013) by resampling and averaging elevation for each grid square, are used to represent the surface routing network. The location of river channel links in SHETRAN are calculated using the minimum elevation DEM opposed to the average DEM as it has been shown that this generates a more accurate representation of the river network (Lewis et al., 2018).

Subsurface processes in SHETRAN are represented as a single column per grid square of multiple layers. The GIS layers containing the soil parameters used in SHETRAN (soil depth, Saturated water content, residual water content, saturated conductivity (m/day), VanGenuchten-alpha (cm-1), and VanGenuchten-n) were taken from the European Soil Database V2.0 (Liedekerke et al., 2006). Structural soil information including topsoil texture, depth to textural change, dominant subsoil texture, and depth to bedrock were also taken from the ESDB and combined into one unique soil raster file for use in SHETRAN. The ESDB is a Europe-wide, 1km resolution standardised database of values of soil particle size and hydraulic properties by fitting Maulem-van Genuchten model parameters to previously existing datasets of soil hydraulic properties. Each grid square column is underlain by a depth of 20m of bedrock which data was sourced from the British Geological Survey BGS) 1:625,000 hydrogeological map (British Geological Survey, 2014). In the case of the Test catchment, four hydrogeological bedrock types were identified with most of the catchment in the upper reaches being defined by highly productive aquifer with most flows through fractures and other discontinuities by virtue of the chalk bedrock. There is reduced groundwater dominance in the lower reaches of the Test catchment (downstream of Abbotswood) due to the presence of Barton clays, sands and silts leading to a designation of essentially no groundwater, low and moderately productive aquifer moving southwards. The parameters used to denote subsurface water transfer within the SHETRAN model are shown in Table 12.

The landcover map was used as provided in the automated setup, with a 1km gridded version of the Centre for Ecology and Hydrology (CEH) Landcover Map 2007 (LCM2007). This equates to the original 23 land cover types of the LCM2007 simplified to the seven basic land cover types typically used in SHETRAN (arable, bare ground, grass, deciduous forest, evergreen forest, shrub, and urban (Birkinshaw, 2011). The LCM2007 is derived from remotely sensed satellite imagery and digital cartography using land cover classifications based on the UK biodiversity Action Plan Broad Habitats. The parameters used within SHETRAN for the different land cover classifications are detailed in Table 13.

Table 10 SHETRAN data file inputs. New rainfall and PET time series are highlighted in blue.

Data type	**Source**	**Description**	**Reference**
River Test catchment boundary	National River Flow Archive	The NRFA holds shapefiles of 1170 UK catchment boundaries	(Morris et al., 1990)
Land Cover Map 2007	Centre for Ecology and Hydrology (2012)	1 km raster	(Morton et al., 2011)
Soil map created from the European Soil Database layers	European Commission and Joint Research Centre (2012)	Four 1km rasters	(Liedekerke et al., 2006)
Hydrogeology map	British Geological Survey (2012)	Shapefile	(British Geological Survey, 2014)
Land-form PANORAMA Digital Elevation Model	Ordinance Survey (2012)	50m raster	(Ordnance Survey, 2013)
Flow data timeseries	National River Flow Archive (2012)	Individual .csv files	(Fry & Swain, 2010)
Rainfall time series	CEH-GEAR daily and monthly rainfall for the United Kingdom	1km gridded .netCDF files	(Tanguy et al., 2019)
Potential Evapotranspiration time series	CHESS-PE climate hydrology and ecology research support system potential evapotranspiration dataset for Great Britain	1km gridded .netCDF files	(Robinson et al., 2020)

Table 11 Summary table of SHETRAN input files generated from the source datasets.

Layer	**Description**	**Source data**
Minimum DEM	DEM approximating the minimum elevation value in each resampled grid square. Used to generate elevation (m)	OS Land-form PANORAMA DEM
Average DEM	DEM generated from the mean elevation value in each resampled grid square. Used to generate elevation (m)	OS Land-form PANORAMA DEM
Soil and geology	Approximates the sub-surface as a column with multiple layers of soil or rock for each grid square.	European Soils Database and BGS hydrogeology map.
Land cover	Represents vegetation cover in each grid square.	CEH LCM 2007

Table 12 A table to show the parameter values for sub-surface water transfer within the SHETRAN model. Soils (orange) and hydrogeological water transfer (blue) use the same combination of water transfer parameters (soil depth, saturated water content, residual water content, saturated conductivity and vanGenuchten alpha and n) with different values. Parameter values for soils are derived from the European Soils Database (Liedekerke et al., 2006) and hydrogeological values were derived from the Hydrogeology 625k shapefile from the British Geological Survey (British Geological Survey, 2014).

	Soil Type	**Soil depth at base of layer (m)**	**Saturated water content (%)**	**Residual water content (%)**	**Saturated Conductivity (m/day)**	**VanGenuchten – alpha (cm-1)**	**vanGenuchten-n**
Soils	Coarse	1.2	0.403	0.025	60.000	0.0383	1.3774
	Medium	0.4	0.329	0.010	10.755	0.0249	1.1689
	Fine	1.0	0.481	0.010	8.500	0.0198	1.0861
	Very Fine	1.0	0.538	0.010	8.235	0.0168	1.0730
Hydrogeology	No Groundwater	20.0	0.300	0.200	0.0001	0.010	5.0000
	Moderately Productive Aquifer	20.0	0.300	0.200	0.010	0.010	5.0000
	Highly Productive Aquifer	20.0	0.300	0.200	50.000	0.010	5.0000

Table 13 The parameters (Canopy storage capacity, Leaf Area Index, Maximum root depth, Actual/Potential Evaporation at field capacity, and Strickler overland flow roughness coefficient) for land cover and the specific values used for each land cover classification. Land cover data is from the Centre for Ecology and Hydrology Land Cover Map 2007 (Morton et al., 2011).

Land Cover type	Canopy Storage Capacity (mm)	Leaf Area Index	Maximum Root depth (m)	Actual/Potential Evaporation at field capacity	Stricker overland flow roughness coefficient
Arable	1.5	1.0	0.8	0.9	1.5
Bare Ground	0.0	0.0	0.1	0.8	2.0
Grass	1.5	1.0	1.0	0.9	1.0
Deciduous Forest	5.0	1.0	1.6	1.0	0.5
Evergreen Forest	5.0	1.0	2.0	1.0	0.5
Shrub	1.5	1.0	1.0	0.8	1.0
Urban	0.3	0.3	0.5	0.8	5.0

5.2.2 Flood metrics

The SHETRAN model outputs a streamflow timeseries from a channel node specified by the user. It is not a 2D hydraulic model, and therefore does not provide information about flood extent or depth in the flood plain. It also does not measure the location, extent, and depth of groundwater emergence (Birkinshaw, 2011). This modelling study focuses on groundwater induced floods where intense groundwater discharge from springs and highly permeable shallow horizons contribute to surface water channel flows and cause bank overtopping. Therefore, changes in floods before and after NFM implementation are represented in terms of streamflow characteristics. The four metrics chosen were: change in peak flood magnitude, the change in flood duration, the number of flood incidences, and the percentage of time banks were overtopped. A measure of the changes in flood peak are a typical output from NFM flood modelling studies, with success usually being measured as a significant reduction in the peak (SEPA, 2015). This is because significant flood peak reductions are often linked with a reduction in bank overtopping, as well as a reduction in the extent and depth of surface runoff generation. Some NFM studies focus on a single flood event from a design flood hydrograph and measure the change in shape and timing of the output hydrograph. This study focuses on a long time series including multiple flood events using observed data to understand the potential impact of implemented NFM in groundwater-dominated catchments on the overall catchment function and the effect of NFM on a range of actual flood magnitudes.

Flood duration was included as a metric due to the unique properties of groundwater-dominated floods. Because groundwater floods generally occur at the rate of the water table rising, groundwater flooding rarely causes loss of life. Damages are mostly associated with long flood durations causing disruptions to infrastructure and transport, as well as damage to properties (Cobby et al., 2009; Hughes et al., 2011; Morris et al., 2007). Therefore, this is an important additional dimension to flood analysis in these catchments. If flood peak reductions do not generate a significant reduction to flood duration as well, floods are still likely to be highly disruptive.

The final metrics are the number of flood incidence and the percentage of time that banks are overtopped. These two metrics should be examined together to gain a full understanding of changes to flood structure. There can be instances where flood peak reductions may translate to an increased flood incidence, due to shorter periods of bank overtopping (e.g., a 14-day flood becoming two shorter 3-day floods in the same 14-day period). This would therefore be reflected in the reduction in the percentage of time overtopping. The same is true where banks are overtopped more consistently, generating fewer floods but increasing the percentage of time the banks are overtopped.

The combination of these flood metrics provides an understanding of changes to flood hydrology. Analysing multiple flood events over a long period of time will give greater insight into the effect that NFM has on a range of different flood magnitudes. The period 1990 to 2017 was chosen because it includes two major groundwater flooding events (2000/01 and 2014), as well as multiple smaller but notable flood events (1995, 2003, 2007). This will give insight in to how NFM alters groundwater-dominated flood response, as well as how meaningful these changes can be in reducing disruptions caused by long duration floods.

5.2.2.1 Selected flood thresholds and gauge locations

To estimate the number of flood incidences, the percentage of time banks are overtopped and flood duration, a bank overtopping flood threshold is required. The stage at which banks are overtopped are recorded in multiple locations throughout the Test catchment on the government flood information and warnings website (Check For Flooding GOV.UK, 2021) and the River Levels UK website (River Levels UK, 2021). These stage estimates are described as ‘a typical high’ meaning that at or above these stages flooding has historically occurred and is therefore likely. To translate these stage overtopping values in to discharge (compatible with SHETRAN outputs) stage-discharge rating curves were developed.

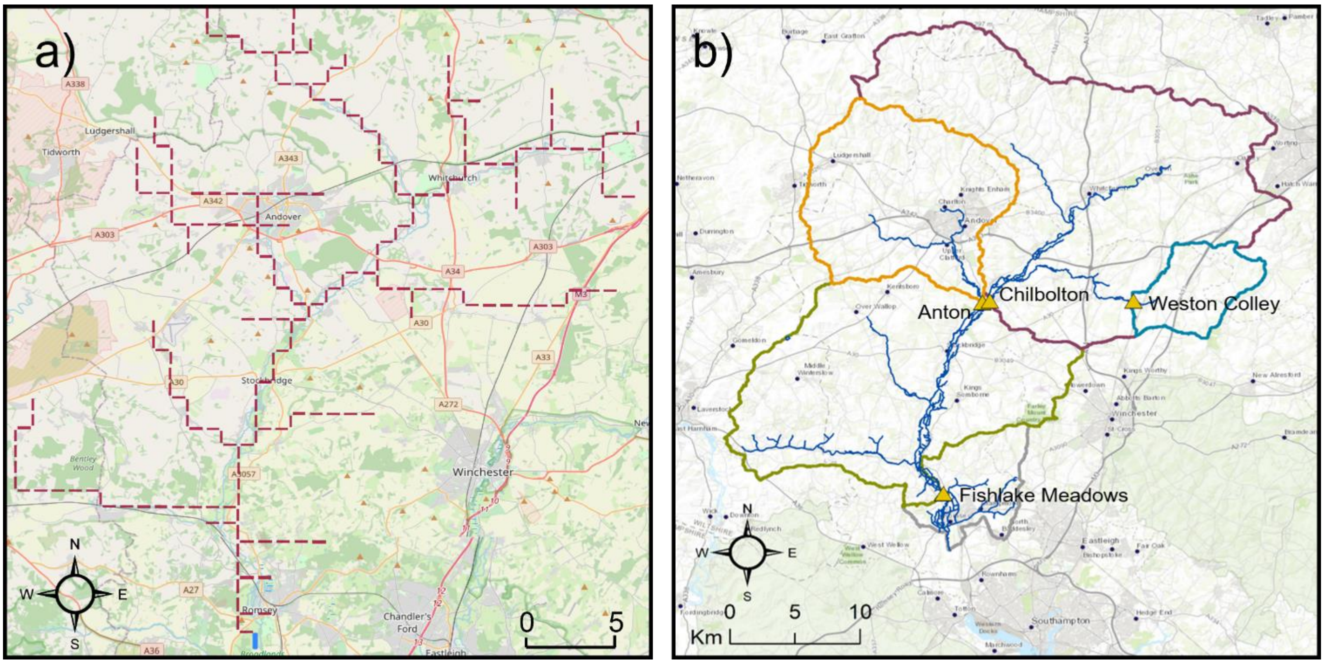


Figure 21 a) Channel network discretisation of the River Test in the SHETRAN model (figure and base map obtained from the ‘SHETRAN Results Viewer’ tool currently under development at Newcastle University). b) Catchment map of the River Test its sub-catchments and gauge locations.

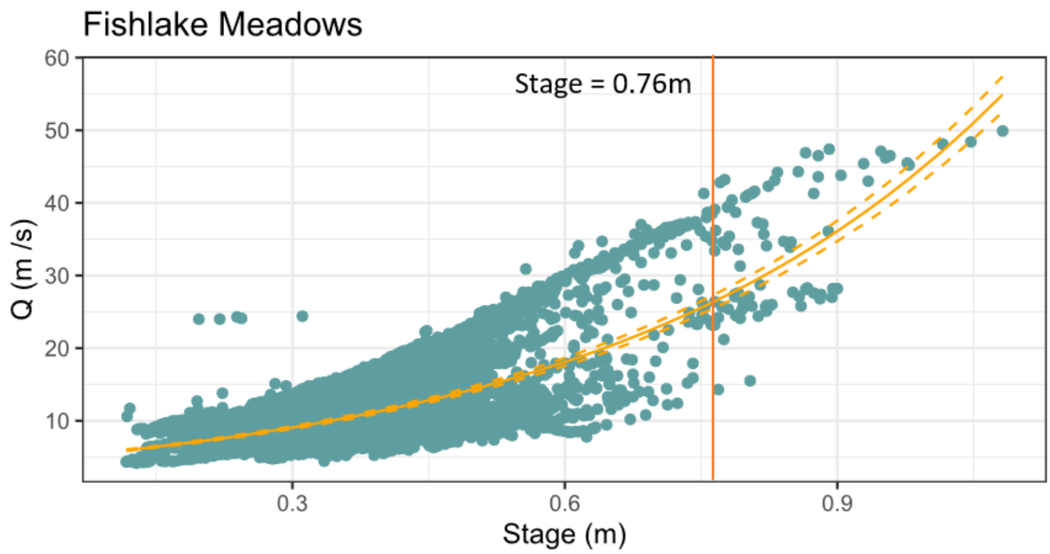
Data availability of suitably long or overlapping stage and discharge data significantly limited the choice of gauges. The three gauges with sufficient data were Fishlake Meadows, Anton and Chilbolton (Figures 21). Multiple gauges were chosen throughout the Test catchment because of the known scale effects of NFM (Dadson et al., 2017). Having multiple gauges for sub-catchments, mid-stream and downstream will give an understanding how NFM interacts with streamflow at multiple catchment area scales throughout the catchment. The Weston Colley gauge (Figure 22) was included as a flow outlet in SHETRAN despite a lack of available data to develop a rating curve. This is because the Anton gauge was the smallest Test sub-catchment with sufficient data to develop a rating curve.

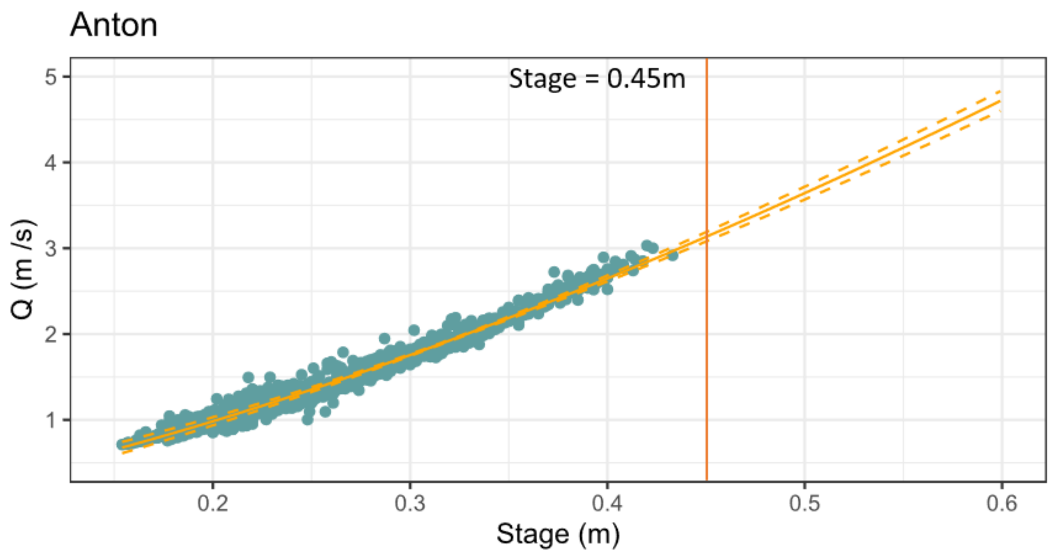
At 185 km^2, this is much larger than the evidence base suggests that NFM is most effective at >20 km^2 (Dadson et al., 2017). Weston Colley is a smaller catchment at 52 km^2. Whilst this is still too large, it may be more suitable for testing and measuring the effects of NFM. Because there was insufficient data to develop a rating curve at this site, results will be measured in terms of changes to flood peaks only at Weston Colley. This therefore gives an incomplete picture of NFM interactions at this site, but it was thought prudent to include in the analysis due to the evidence base suggesting that optimum NFM benefits will not be achieved at larger catchment scales.

Discharge time series were obtained from the National River Flow Archive (NRFA) and stage data from the River Levels UK website (Fry & Swain, 2010; River Levels UK, 2021). These datasets were used to generate stage-discharge relationships by fitting curves to the data using the 'nls' package in R (Baty et al., 2015) which is a tool for fitting non-linear regressions to data. Linear, polynomial, and exponential linear models were fitted against each dataset and the model ultimately chosen for each gauge dataset had the highest R^2 and the smallest standard error. The standard error of the regression was calculated using the same R package and 95% confidence intervals were estimated (Figure 23).

Table 14 Discharge flood thresholds derived from stage-discharge rating curves

Gauge	R^2 of linear models	'Typical high' stage flood threshold	Discharge flood threshold estimate (Threhsold = bank overtopping)	Uncertainty in discharge estimate based on the standard error of the linear model	NRFA 5% annual exceedance
Fishlake Meadows	0.518189	0.76	26.1	+/- 2.3 (8.81 %)	24.0
Anton	0.972464	0.58	4.5	+/- 0.1 (2.2%)	3.7
Chilbolton	0.520559	1.45	12.6	+/- 0.4 (3.1%)	10.5


Fishlake Meadows
Stage = 0.76m
Q (m /s)
Stage (m)
60
50
40
30
20
10
0.3
0.6
0.9


Anton
Stage = 0.45m
Q (m /s)
Stage (m)
5
4
3
2
1
0.2
0.3
0.4
0.5
0.6

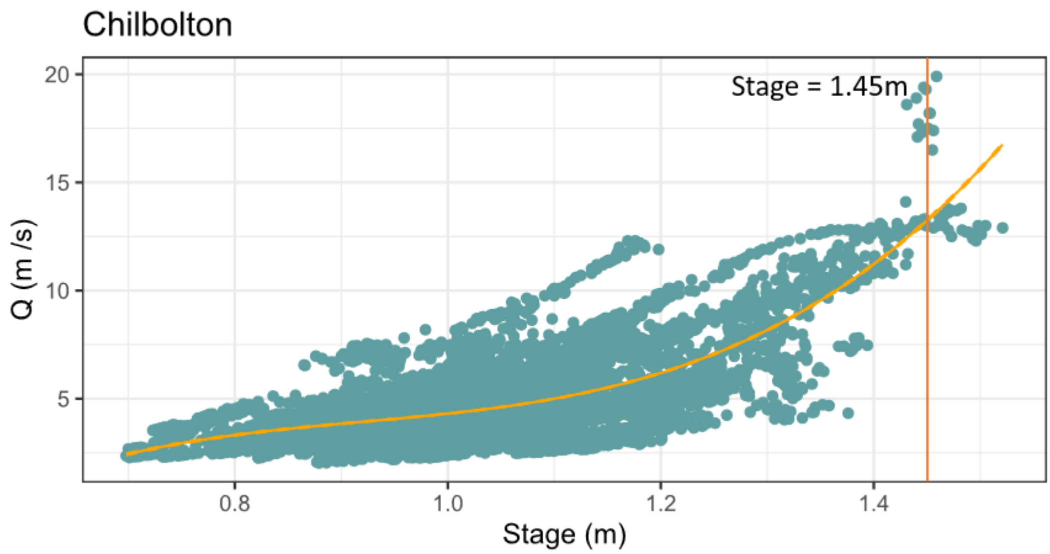

Chilbolton
Stage = 1.45m
Q (m /s)
Stage (m)
20
15
10
5
0.8
1.0
1.2
1.4

Figure 22 Rating curves developed using fitted lines to stage and discharge data for the gauged sub-catchments in the River Test study area. 95% confidence intervals and the bank overtopping threshold stage are included.

These bank overtopping stage thresholds were then verified using known flood dates from the Chronology of British Hydrological Events (Black & Law, 2004) historical floods record and a local flood dates record compiled and supplied by colleagues at the Romsey branch of the Environment Agency. The bank full thresholds from the developed rating curves were compared to measured discharges on the flood dates at each gauge. Using the linear model of the fitted curves, discharge threshold estimates and an associated 95% uncertainty margin were derived from the stage thresholds, and recorded in Table 14. These estimates were then sense checked against flow frequency probabilities recorded in the National River Flow archive. Where the derived bank overtopping discharge estimates were higher than the 5% exceedance probability recorded in NRFA, the flood threshold was accepted.

It is acknowledged that significant uncertainties are associated with using a stage-discharge rating curve. One of the sources of uncertainty is the discharge estimates at the three gauges. A crump weir is located at the Anton gauge which reduces the impact of changes in cross-section or vegetation. However, at this site the NRFA notes that water levels are manually altered by a local mill sluice and eel traps which will further reduce the accuracy of the flood threshold calculated at this gauge. This is reflected in the 7.2% sensitivity of the gauge (National River Flow Archive, 2021) noting an almost 10% uncertainty in the flow records due to uncertainties in the control stage estimates. Both the Fishlake Meadows and the Chilbolton gauges have reduced uncertainty due to being higher accuracy doppler and electromagnetic gauges respectively. Whilst both of these gauges require maintenance to reduce inaccuracies that may be caused by sedimentation or seasonal vegetation growth, neither of these gauges note issues with this and it can be fairly assumed to be well maintained (National River Flow Archive, 2021). Additional uncertainties can be caused by fitting linear models to the stage-discharge data; however, this has been minimised by testing multiple regression algorithms and choosing the one with the highest R^2 and smallest standard error. The impact of this uncertainty on the flood discharge threshold estimate is recorded in Table 14. The uncertainty in these estimates is reduced by sense checking the flood threshold estimates with observed discharges (assuming reasonably accurate flood discharge estimates at the gauging sites) on known flood dates. To further mitigate the potential inaccuracy of the flood threshold, all NFM model scenarios are compared to a baseline model run as relative changes, which maintains the same uncertainties across each model simulation.

5.2.2.2 Model setup and calibration

The SHETRAN model of the Test catchment as provided by Lewis et al. (2018) included all of the required input files including: an ascii file mask of the catchment (equivalent to the catchment boundary), minimum and average DEMs of the Test catchment (used to calculate overland flow and the river network) as ascii files, a soil and hydrogeology layer in ascii format, a land cover map based on LCM2007 as an ascii, and six year time series (2000-2006) of rainfall based on the UKCP09 rainfall data and a time series for the same time period of PET derived from UKCP09 climate data using the Penman-Monteith method. As stated in section 5.2.1.2, the run time of the model was extended from to 1990-2017 to include more floods and the originally provided rainfall and PET were replaced with the CEH-GEAR gridded daily rainfall and the CHESS PE datasets. Aside from rainfall and precipitation datasets, all other input datasets were kept the same as those provided in the automated setup of the Test catchment. SHETRAN was provided in its simplest form, with a zero-flow boundary at the catchment boundary meaning that no surface or subsurface water inputs come from outside of the topographic Test catchment boundary. In reality, the groundwater catchment boundary drains from the wider Hampshire chalk catchment (Stuart & Smedley, 2009), but the topographic catchment boundary was maintained for simplicity.

The CEH Land Cover map 2007 provides the required information about the spatial variation, density, and type of land cover. These vegetation types are then used to assign information such as stomatal resistance and interception properties in the Evapotranspiration module in SHETRAN and root depth and in the variably saturated sub-surface module. Although the CEH Land Cover Map 2015 was also available, the LCM2007 map provided was thought to be adequate as its classes and spatial resolution of data available were the same between the two datasets. Therefore, the plant properties assigned to the same classes from both LCM datasets will be the same in SHETRAN for either dataset. Any differences in the datasets in terms of SHETRAN modelling will be due to differences in spatial allocation of classes between the two LCM datasets. These are likely to be minimal as small changes in the classification algorithm used between the two datasets are unlikely to have significant impacts at the 1km scale (NERC & CEH, 2017). Given that LCM2007 encompasses the period between 1990-2017 and land cover will have inevitably changed during this period anyway, the LCM2007 was concluded to be adequately accurate for this study.

The soil map provided by Lewis et al. (2018) represents all sub-surface flows as a stacked column of multiple different depths and textures representing all processes from surface material to bedrock geology and hydrogeology. The arbitrary depth of 20m of bedrock was maintained in the model setup. Although the chalk bedrock in the Hampshire basin is significantly deeper than this, varying between 200 and 560m total thickness (Aldiss 20212), it is the upper chalk layer that contributes to stream flows (Headworth, 1978). This 20m bedrock layer is represented as a single porosity matrix in SHETRAN, as opposed to the dual porosity bedrock present in the Hampshire basin. However, this is accounted for by the inputs from the BGS Hydrogeology 625k layer which approximates flows controlled by fissures and discontinuities (Brisitsh Geological Survey, 2014). Whilst the location of specific fracture flow is not represented in this version of the SHETRAN model, the overall effect of these features on the water table height and groundwater contributions to streamflow are suitably represented by the British Geological Survey Hydrogeology map (British Geological Survey, 2014).

Using this model setup, baseline model runs were conducted to measure the accuracy of the SHETRAN model as provided by the automated setup by Lewis et al. (2018) with the alternate rainfall and PET data. The comparison of simulated flow estimates with observed gauged flows shows that the model overall slightly underestimates extreme peaks and overestimates low flows (Figure 24). This is most pronounced at the Anton gauge and is reflected in the Nash-Sutcliffe coefficient for this gauge (Figure 24). Observed flows at the Weston Colley gauge are systematically overestimated by approximately 0.4 m^3/s which is also represented as a negative Nash-Sutcliffe coefficient. This is likely due to the stability of the model requiring greater flows within the river network. As flows in the headwaters of the model river network are calculated as an accumulation of upstream areas, headwaters may be overestimated due to an incorrect drainage area due to the coarse spatial resolution of the DEM. This could also be due overestimated rainfall or underestimated PET at these sites. The simulated flows at the Anton gauge may also suffer from this, though it is also likely that the model does not represent the impact of Andover town upstream of the gauge, causing the peaks to be underestimated due to underrepresentation of surface runoff, and low flows to be overestimated due to over estimation of groundwater influence in this location. Overall, the SHETRAN modelled flows fit the observed data very well, with timings being represented accurately and peaks being in the correct order of magnitude relative to other flows. Whilst flows at Weston Colley are systematically overrepresented, the fit of the observed and modelled flows is very good. The initial conditions were experimentally varied (in SHETRAN the initial conditions represent the depth of the water table below the ground surface), but it was found that altering this variable simply caused an increase in the run-in period from 2 years to 3-4 while the model stabilised. Therefore, the model was used as it is currently calibrated and with the setup as detailed above.

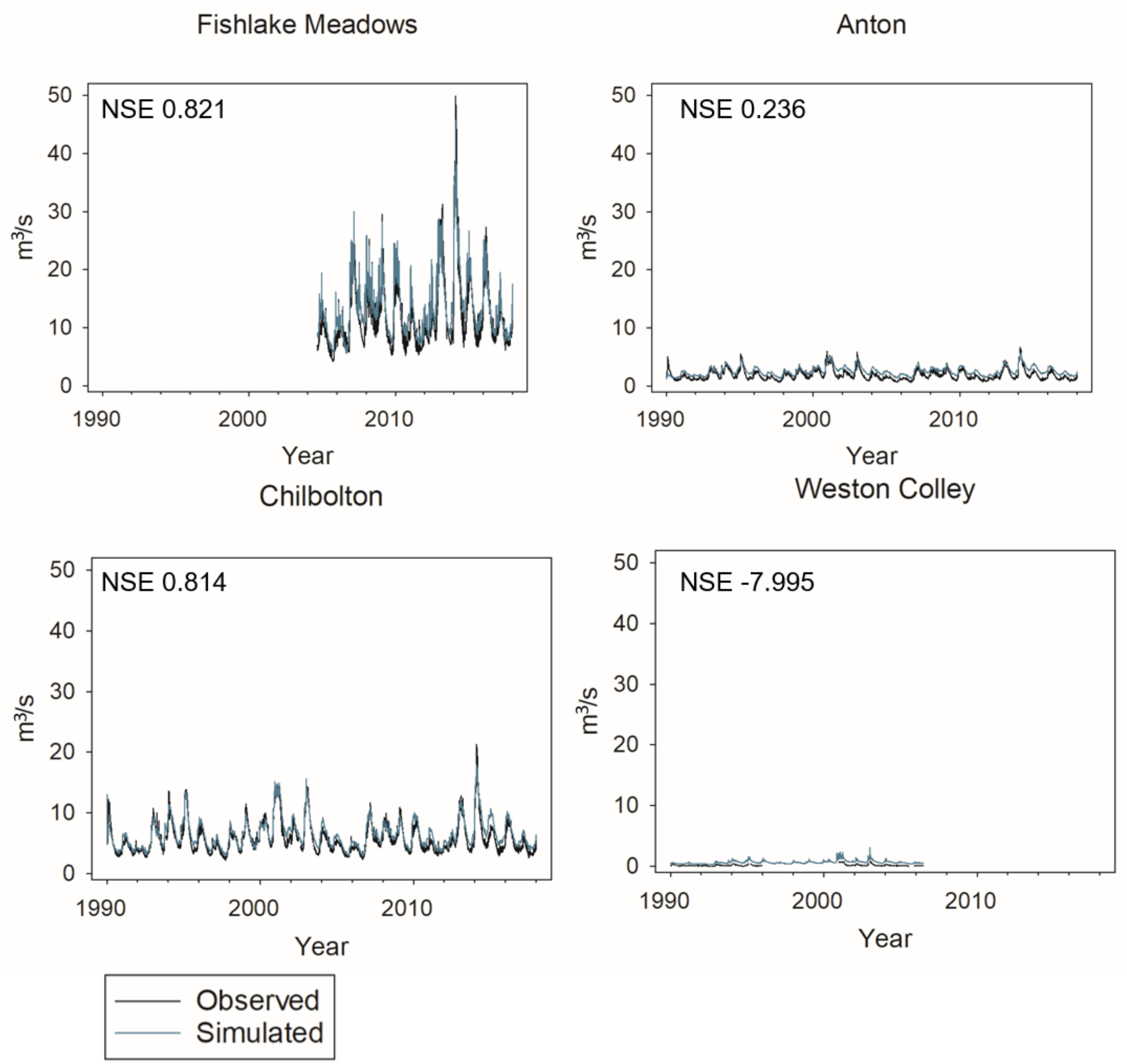


Figure 23 Comparison of observed (black) and simulated (blue) flow estimates for all gauges on the River Test, including the Nash-Sutcliffe estimates for each gauge.

Considering the potential impact of compounding uncertainty from the flood threshold estimates (section 5.2.2.1) and the general underestimation of flood peaks via SHETRAN simulations, it was decided that all model scenarios would be measured against a modelled baseline. This allows the analysis of relative changes within the SHETRAN model due to NFM changes represented in the model. Therefore, all model outputs were analysed through the lens of potential relative changes that could be affected in a generic groundwater-dominated catchment (using the Test catchment as an example) rather than as an assessment of absolute values in the Test catchment.

5.2.3 Representing NFM in SHETRAN

The SHETRAN model was chosen primarily because it provides the capability of representing groundwater-dominated flow processes required for chalk catchments, and because it can represent different channel and catchment based NFM measures. Because SHETRAN calculates overland and channel flows at a 1km grid scale, the representation of some NFM interventions which work (hydraulically) on a scale below 1km is negated. Most notably, the spatial resolution cannot accurately represent additional surface water storage in a catchment. Generating storage ponds are a common NFM measure most often represented in hydraulic models by altering the model's elevation surface to generate topographic low points (Callow & Smettem, 2009; Hankin et al., 2019; Metcalfe et al., 2017; Robotham et al., 2021; Samra, 2017). In this case, modifying the catchment DEM can only occur at the 1km scale and would not be representative of a small storage pond (often only a few meters wide). There is the capability of representing catchment storage as mediation of flow via the 'lakes' module in SHETRAN. The smallest scale this can be represented at is the 1km grid scale which is not representative of NFM storage ponds. Given that groundwater-dominated catchments are defined by a large quantity of aquifer storage and reduced surfaces runoff processes, it has already been posited that creating additional catchment storage via relatively small storage ponds is unlikely to have a significant mitigating effect on groundwater-dominated flooding (Barnsley et al., 2021).

In-channel interventions were found to be the most viable and promising NFM interventions for highly groundwater-dominated catchments (Barnsley et al., 2021). Additionally, work completed in Chapter 4 demonstrates that river restoration has been the focus for management on the River Test and most other chalk streams over the past decade, often with work being partially justified via potential flood reductions brought about by the works (The Environment Agency, 2013). Given the current lack of evidence, it is therefore important to establish the potential effectiveness of in-channel NFM interventions on flood flows in these river catchments. Model scenarios of in-channel NFM seek to ascertain the effect on flooding of the implementation of the Test and Itchen River Restoration management plan, as well as the result of revegetating the river channel. Individual features cannot be represented hydraulically within the SHETRAN model. In-channel NFM is therefore represented within SHETRAN as reach-averaged roughness values, an approach often taken to model in-channel NFM (Addy & Wilkinson, 2019). Roughness values used for model parameterisation are based in field-estimated values, as outlined in Chapter 4.

The creation of deciduous woodland was chosen as the land based NFM intervention in this study. The woodland creation scenarios in this suite of models are based on woodland creation research and opportunity mapping for NFM purposes completed and provided by the Forestry Commission's Forest Research (Broadmeadow et al., 2014). Woodland creation can alleviate flooding in 3 main ways (Thomas, 2018):

1) high water use of trees increases the available soil water storage and can reduce surface runoff,
2) high infiltration in woodland soils reducing direct surface runoff, delaying the passage of water into the river channel,
3) hydraulic roughness by physical obstruction caused by physical obstruction of trees and roots.

Research also suggests that placement of woodland in flow pathways increases their effectiveness as a flood reduction strategy (Thomas, 2018). This approach can be highly effective. Huang et al. (2003) found that increased woodland coverage up to 80% of the catchment area reduced flood peak by 32%. Additionally, increasing the tree coverage in the landscape has also been linked with further benefits, including protecting soils from erosion, retaining nutrients in the land scape, and improving water quality by retaining sediment and stopping it entering water bodies (Samantha Broadmeadow & Nisbet, 2010; Valatin et al., 2022). The UK government has acknowledged the economic, social and environmental benefits of woodland and has set target to increase UK woodland coverage from 13% to 15% by 2050 (Iversen et al., 2021). Along with this, the government have pledged to work with landowners, farmers and key stake holders to increase woodland area in the UK (DEFRA, 2018) meaning there is government support and financial incentives for woodland creation for any purpose. This makes woodland creation for NFM an attractive and popular choice because there is often financial support and widespread approval, making them relatively easy schemes to execute.

Deciduous woodland was chosen for this study because this is the type of woodland that was mapped by Forest Research for the Test catchment (Broadmeadow et al., 2014). This map was used to ensure that simulated woodland creation was within the scope of what is realistic within the Test catchment. Interception losses of deciduous woodland are 10-15%, reduced further to 5-10% during leafless periods, compared to 24-25% for coniferous woodland and are therefore less effective at reducing flooding (Forest Research, 2022). Deciduous woodland was chosen by Broadmeadow et al. (2014) because it was found previously that widespread plating of coniferous woodland was not accepted by landowners and other stakeholders involved in woodland planting schemes because they are not currently common to the chalk lowland landscape (Samantha Broadmeadow & Nisbet, 2010).

5.2.3.1 Sensitivity analysis

A sensitivity analysis was conducted to ensure that the SHETRAN model is sensitive to changes in channel network link Manning's *n* roughness and deciduous tree cover. This is to ensure that such changes generate a measurable change in output flows.

5.2.3.1.1 Sensitivity analysis of changes to SHETRAN roughness parameter

Roughness values in SHETRAN are coded using the Strickler coefficient, the inverse of the Manning's *n* roughness coefficient (Birkinshaw, 2011). The SHETRAN model was tested for its sensitivity to changes in roughness within the range that was obtained via the literature and validated using field data (see Chapter 4). This range of manning's *n* values (0.03-0.625) was converted into a range of Strickler coefficient values (33.33 – 1.6 respectively). This range was divided by 5 to generate 5 different Strickler values (Table 15) which were then applied universally to the Test catchment SHETRAN river network. The output flows at the Fishlakes Meadows gauge were then compared for the model sensitivity to varying roughness coefficients. The lowest downstream gauge was chosen because it represents changes across the whole catchment.

Table 15 Roughness sensitivity analysis scenario designs. The roughness range was derived from field estimates and the literature. The difference between the highest and lowest values were divided by five to generate five incremental increases in roughness values.

Sensitivity scenario	Manning's *n* coefficient	Strickler Coefficient for SHETRAN
High roughness	0.625	1.6
Medium high roughness	0.105	9.53
Medium roughness	0.057	17.46
Medium low roughness	0.039	25.39
Low roughness	0.030	33.33

For ease of analysis, Figure 25 was plotted for the upper and lower roughness scenarios. The effect of increasing roughness to the highest value results in an 8% reduction in peak flows, whilst hydrograph shape and flood peak timing remain similar. This analysis demonstrates that the model in this setup is sensitive to changes in the Strickler coefficient within the range found for chalk stream reaches that have undergone different level of restoration.

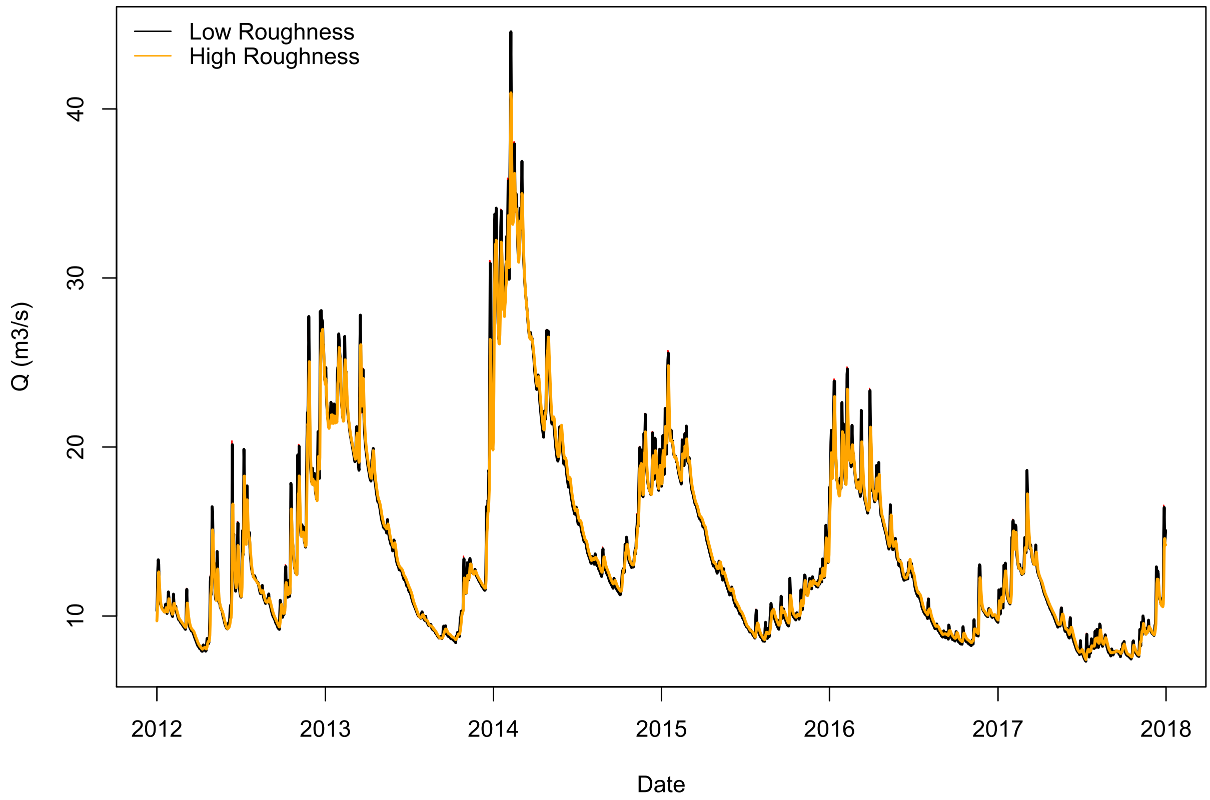


Figure 24 Roughness sensitivity analysis output at Fishlake Meadows gauge. This demonstrates an overall reduction in peak flows under the higher roughness parameterisation of the model, indicating that the model is sensitive to altering the roughness values of the modelled river channel.

5.2.3.1.2 Sensitivity analysis of SHETRAN to changes in deciduous forest cover

The SHETRAN model was also tested for its sensitivity to landcover changes. From the LCM2007 dataset, there are seven land cover classifications in the SHETRAN model: 1) arable, 2) bare ground (0%), 3) grass, 4) deciduous forest, 5) evergreen forest, 6) shrub, and 7) urban. In the Test catchment the land use types found are arable (67.7%), grass (22.7), deciduous (5.8%) and evergreen (0.3%) forest, and urban (3.5) land uses. The sensitivity of the SHETRAN model was tested for changes in the proportion of deciduous forest.

For this analysis, the original coverage of deciduous forest was increased three times in areas surrounding the original coverage, until the full catchment area was classified as deciduous forest (Figure 26). The Forest Research opportunity map recommends up to 27.5% coverage of the Test catchment and this sensitivity analysis was set up to ensure that the SHETRAN model is sensitive to this scale of woodland conversion in the modelled Test catchment. Up to 100% coverage of deciduous forest was included in this sensitivity analysis as a theoretical exercise. Most other woodland creation for flood management studies test a much greater proportion of the catchment (e.g., 80% coverage in Huang et al. 2003). The new raster files were generating by manually digitising polygons around the original forest coverage and increasing the coverage for each step in ArcMap 10.8. Using the 'Extract by Mask' tool in the 'Spatial Analyst' toolbox, ArcMap, these polygons were used to extract an area of the land cover map which was then reclassified as deciduous woodland. These new raster files were then re-integrated with the land cover map using the 'Mosaic to new Raster' tool in the 'Data Management' toolbox. Step 2 and 3 represents an approximate 20% increase in deciduous forest coverage, whilst step 1 represents a 38% area increase in deciduous woodland.

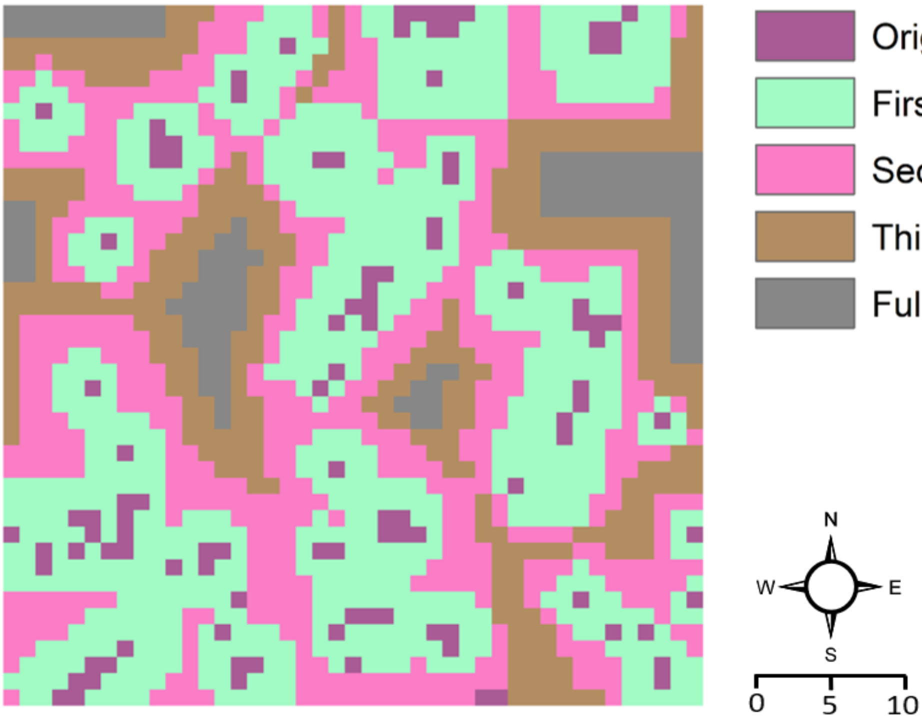


Figure 25 Deciduous Forest coverage for sensitivity analysis scenarios. The area covered by deciduous forest was increased around the original areas covered incrementally until the whole catchment was defined as deciduous forest.

Figure 27 demonstrates that SHETRAN is sensitive to increasing the area covered by deciduous woodland, with an average 13% flood peak reduction and maximum 21% for the full coverage scenario. The most marked reduction in discharge occurs from the original forest cover to step 1 due this being the greatest increase in woodland area (30% coverage for step 1, with a 5.8% original coverage), with an average 6% flood peak reduction with a maximum of 12%. Each subsequent increase in deciduous woodland area sees flow reductions, but at smaller increments. The most marked reductions in flow occur at flood peaks. Therefore, SHETRAN is sensitive to incremental increases in deciduous woodland cover and can represent land cover NFM manipulations.

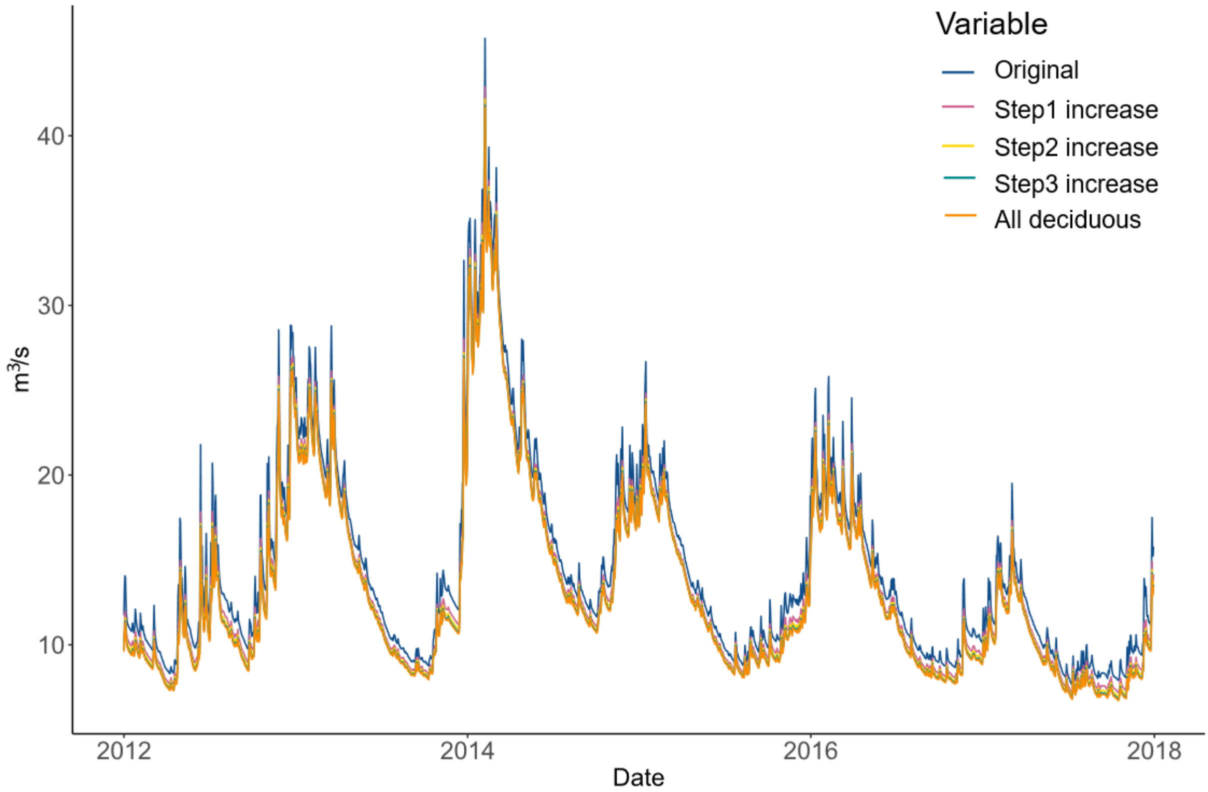


Figure 26 Results for the deciduous forest land cover sensitivity analysis. As the area covered by deciduous woodland increases, peak flows reduce indicating that the model is sensitive to changes in the spatial coverage of deciduous woodland.

5.2.3.2 Representing in-channel NFM implementation via river management in SHETRAN

All the scenarios in this suite of models were based on the Test and Itchen River Restoration Strategy (T&IRRS) and the research described in Chapter 4. The T&IRRS assessed the environmental state of the two rivers in 2010 and found to them be in poor ecological and morphological condition. Recommendations were made to improve the hydrological and biological health of the River Test, focussing on changes that would benefit the plant and animal species. In general, recommendations advocated a less intense management style, revegetating the river channel, and implementation of flood strategies like lowering banks and implementing woody debris dams and deflectors (The Environment Agency, 2013). The model scenarios representing in-channel NFM interventions are based on this report and its recommendations for the River Test.

These model scenarios represent changes in management styles and therefore channel complexity. Here, the Manning's roughness coefficients represent the alterations to flow caused by vegetation growth, changing channel bed material, bank material, the amount of bank vegetation, and changes to channel planform (including bank ingress due to vegetation growth, the addition of woody debris in the river channel and bank lowering). River channel management styles, restoration status and NFM implementation affect the type and presence of each of these features. To design each scenario, Strickler values (inverse of the Manning's roughness coefficient) were altered to suit the management style and features of that 1km river reach for each river channel node in SHETRAN.

Roughness values for chalk streams were ascertained via review of the literature and were accepted by comparing them to the field-measured Manning's *n* roughness coefficients ascertained from the work in Chapter 4. River restoration schemes, NFM implementation and changes in management styles occur at a scale often smaller than 1km section of river at a time, each 1km node of the Test catchment network in SHETRAN was broken down in to ten 100m sections. Manning's *n* roughness coefficients were assigned to each 1km river network node using a weighted average, with each 100m river reach getting an equal weight of 1. For each 100m section with varying degree of wildness, that roughness value was given that weight out of 10.

For example:

> 400m high complexity chalk stream with woody deflectors, 600m low complexity chalk stream =
>
> ((0.282 * 4)+(0.028 * 6))/10 = 0.130 Manning's *n* coefficient assigned to network node

Model scenarios represent the concurrent planform changes that occur because of river restoration or NFM implementation. Such changes include bed level raising by inputting clean gravel (a chalk stream river restoration strategy), channel narrowing due to vegetation encroachment and woody debris deflectors and bank lowering to reconnect the channel to the flood plain. In conversations with stake holders, it was found that reduced bank management (especially cessation from mowing banks) often results in a 1m vegetation encroachment on both banks, 2m in total (Table 14). Where bank lowering was implemented, they were often lowered by 0.5m. Therefore, this was set as the value at which banks were lowered, along with the corresponding DEM node adjacent to the stream.

Table 16 SHETRAN roughness input values for high, medium, and low complexity river reaches on the River Test as established via dilution gauging and literature.

Feature	Strickler roughness value	Manning's Roughness value	Ingress due to vegetation growth (m)	Justification	References
Heavily managed (non-complex river reach)	34.5	0.029	0	Based on the value measured at Abbott's Worthy Side stream during field work and the lower end of the roughness range established via literature review.	Clilverd et al., 2016; German & Sear, 2003; Goderniaux et al., 2015; House et al., 2016
Medium management	10.4	0.0965	1	Rectory been boarded section field value and medium vegetated channel/sedge edge respectively	(German & Sear, 2003; Watson, 1987)
Low management (complex river channel) – Heavy vegetation only	5.0	0.199	2	Based on a combined value of heavily vegetated chalk stream as measured in the literature.	(Dawson & Robinson, 1984; Fisher et al., 2003; Watson, 1987)
Low management (complex river channel) – with woody deflectors and other hydraulic obstructions	3.5	0.282	2	Based on values of measured roughness of woody deflectors from the literature.	(Addy & Wilkinson, 2019; Clilverd et al., 2016; Curran & Wohl, 2003; Dixon et al., 2016b; Fisher et al., 2003; Sear et al., 2010; Shields & Gippel, 1993)

5.2.3.2.1 Summary of in-channel NFM model scenarios

Each model scenario was based on the river Test river restoration recommendations from the T&IRRS (The Environment Agency, 2013). It therefore represents changes within the River Test which are achievable, which have been recommended, and that form the strategic plan for the river adopted by all stakeholders engaged in NFM within the catchment.

Baseline scenario: Pre-restoration state of the River Test or the baseline scenario

This is the state that the River Test was in before any of the T&IRRS was implemented. This was inferred by working backwards from the recommendations made in the report (e.g., where channel narrowing, tree cutting, and riparian planting were recommended it was inferred that the channel was over wide and had very little in-channel or bank vegetation). This was represented by changes to the Strickler coefficient only. Bank height and channel width were kept the same as the original model setup. This model scenario was used as the baseline for which all other model scenarios are compared to.

Scenario A1: Current state of the river Test

This was based off the map generated in Chapter 4 in collaboration with practitioners showing the location of all the existing (September 2021) river restoration/NFM projects implemented on the Test and Itchen since 2010, including which measures were implemented. Such measures included the implementation of Large Woody Debris and Woody Deflectors, as well as bank lowering, channel narrowing and raising channel beds via gravel augmentation in some specific locations.

Scenario A2: Blanket application of roughness value that represents 'soft' management styles in the headwater river network

Here, a blanket application of a manning's roughness value of 0.199 (representing 'soft' chalk stream management with no addition of LWD – representing a general change in vegetation structure) was implemented to all headwater sections of the River Test channel network in SHETRAN. To accompany this, in all headwaters, a 2m vegetation ingress and channel narrowing (representing by modifying the channel cross section width by 2m) was also implemented in all areas with a Manning's *n* coefficient of 0.199. This was done to understand whether an overall reduction in channel management in the headwaters has a measurable effect on flood conveyance at the gauging node points downstream.

Scenario A3: Full restoration plan Test

This scenario is a representation of the full application of all recommendations in the T&IRRS, plus a blanket application of a Manning's roughness value of 0.199 for all nodes not otherwise specified. It therefore represents a roughness scenario where the full Test has been managed as recommended with very little interference to vegetation structure in and out of the channel. In locations where bank lowering, channel bed raising or channel narrowing was recommended, this was represented by altering the cross-sectional dimensions of the channel link. Areas recommended for the implementation of woody debris and woody deflectors were assigned a roughness value that added the weighted value of woody debris on top of the baseline 0.199.

5.2.3.3 Representing woodland creation for NFM in SHETRAN

The Forest Research opportunity map provided by Forest Research (Figure 28) contains three layers. The first is NFM priority areas. These are sections of land that have been assigned as a priority for NFM implementation. Whilst it is suggested that these areas are wooded, they may also be suitable for other NFM measures due to being known sources of excess runoff generation which is linked directly to the river channel (Broadmeadow et al., 2014). These regions are typically on the flood plain and situated on agricultural land. Therefore, any woodland creation which may occur in the future will be completed via collaborative relationships and at the landowners' discretion. The second layer is classed as low risk woodland creation. These are areas where afforestation is recommended and where woodland creation is most likely to occur in the future due to having minimal land use constraints. The third layer represents areas which are unsuitable for woodland creation due to constraints such as soil type, or having landscape designations, having land uses that would make woodland creation unfeasible (i.e., urban areas and arable land used for growing crops). All areas marked as woodland creation opportunities are areas where woodland could realistically be planted with the greatest possible advantages and with very few drawbacks. It is therefore a realistic estimate of deciduous woodland creation possibilities, meaning that all scenarios and subsequent NFM benefits are in theory achievable for the River Test catchment.

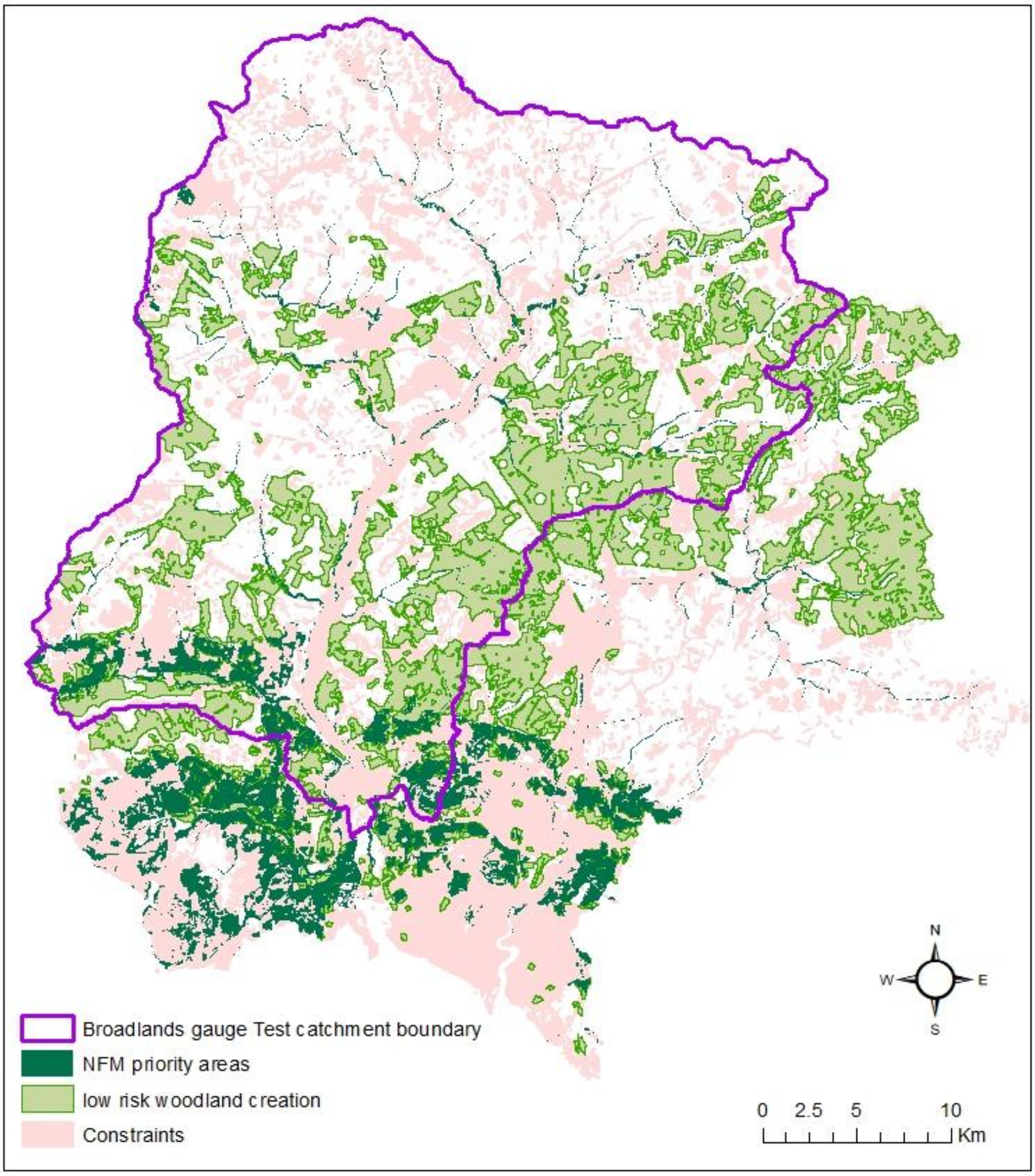


Figure 27 Woodland creation opportunity map for the Test catchment provided by the Environment Agency (Broadmeadow et al., 2014).

Modified land cover SHETRAN inputs were generated by altering the original LCM 2007 SHETRAN input layer according to the woodland creation opportunity map. The woodland creation opportunity map polygons were used to extract their corresponding raster cells from the SHETRAN landcover raster map in ArcMap 10.8. All these raster cells were then reclassified as deciduous woodland using the 'Reclassify' tool and then preferentially merged with the old land use file to generate a new land cover file using the Mosaic to new Raster tool. This was repeated for both the NFM priority layer, the low-risk woodland creation layer and then for a polygon that combined the two layers to generate new landcover inputs files for SHETRAN (Figure 29). All scenarios assume mature tree growth and thus represent the Test catchment up to 40 years post planting.

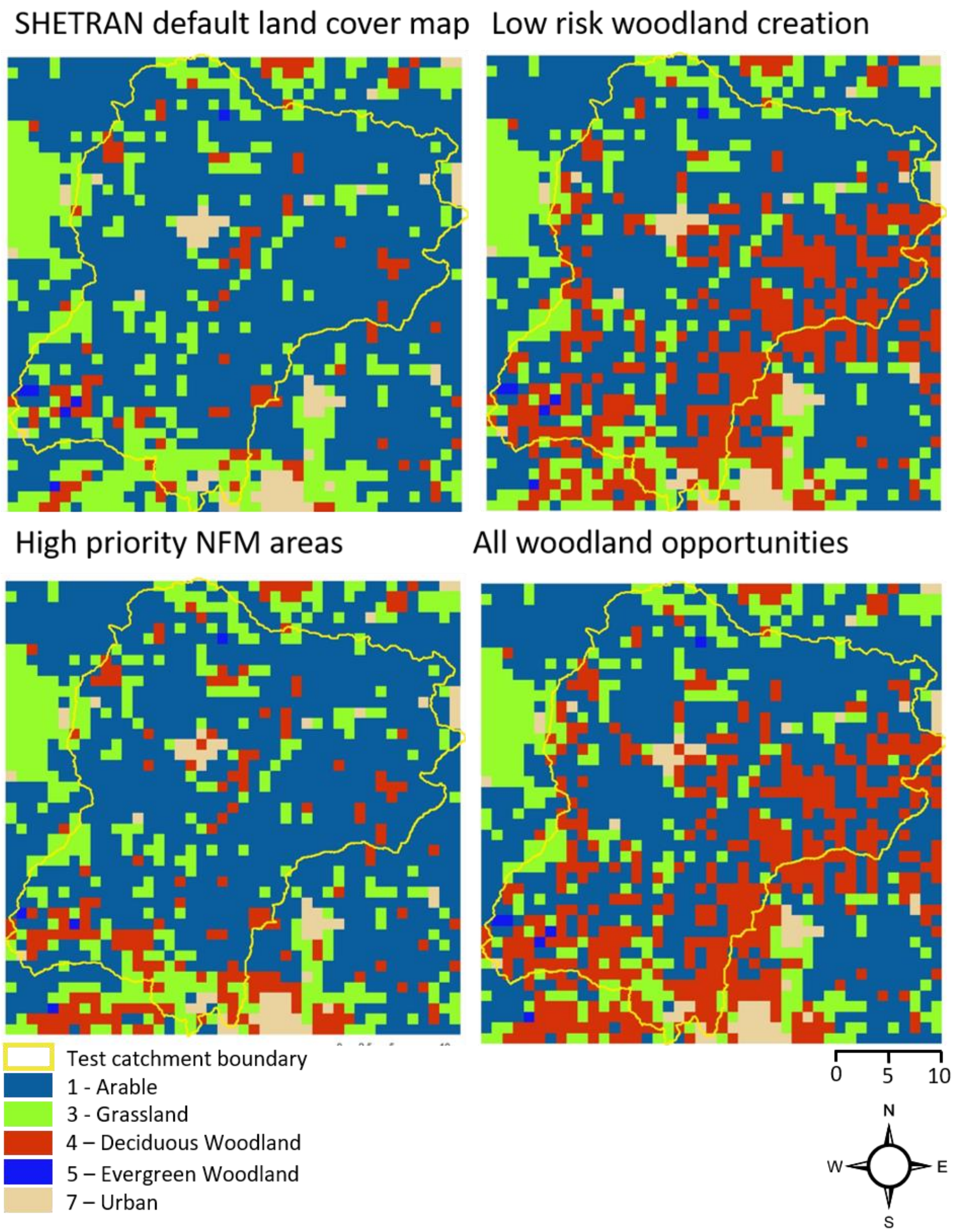


Figure 28 The rasterised landcover which was used as the landcover input to the SHETRAN model generated using the woodland creation opportunity map provided by the Forestry Commission’s Forest Research (Broadmeadow et al., 2014).

5.2.3.3.1 Summary of woodland creation model scenarios

Scenario B1: Woodland creation in areas defined as low risk. The woodland added to these areas are represented as mature trees.

Scenario B2: Woodland creation in areas defined as a priority for NFM implementation. The woodland added to these areas are represented as mature trees.

Scenario B3: The combination of low-risk woodland and NFM priority areas representing all areas recommended for woodland creation in the Test catchment. The woodland added to these areas are represented as mature trees.

To understand the impact of combining NFM measures, woodland creation based on opportunity mapping and in-channel measures were tested using scenarios that combine the two. To reduce the number of simulations, the Wild Test scenario (A3) from the previous suite of scenarios was used because this was the scenario with the greatest flow mitigation. These combined scenarios therefore test the full flood reduction potential of these measures as represented in the SHETRAN model – all other combinations resulting in lower mitigation effects.

Scenario B4: Woodland creation in areas defined as low risk combined with the Wild Test channel roughness parameterisation.

Scenario B5: Woodland creation in areas defined as a priority for NFM implementation with the Wild Test channel roughness parametrisation.

Scenario B6: All areas of recommended woodland creation with the full restoration channel roughness parameterisation.

5.2.4 Model Scenario design for in-channel and catchment-based NFM interventions

Table 17 Scenario designs for modelling NFM implementation in the River Test using SHETRAN model.

Suite	Scenario tag	Scenario name	Description
Baseline	Baseline	Baseline	Baseline SHETRAN scenario with no edits. This is the optimised model run with no in-channel land use or land management changes
In-channel interventions	A1	Current NFM	Changes to Manning's *n* parameters according to stated changes from stake holders and river managers as found in Chapter 4.
	A2	All headwaters soft management	All headwaters and tributaries set to a low management value of 0.199 Manning's *n.*
	A3	Full restoration planned on the River Test	All Manning's *n* values set according to if the whole of the River Test could be rewilded. Manning's *n* values were obtained as if the whole of the T&IRRS was implemented in full.
Woodland creation scenarios	B1	Low risk woodland	All low-risk woodland as currently shown in the shapefile planted and represented as mature trees.
	B2	Priority NFM woodland	Woodland creation added which has been designated as priority NFM woodland creation on top of the baseline parameters
	B3	Combined woodland creation	All woodland recommended in the woodland feasibility shapefile implemented on top of baseline SHETRAN parameters.
	B4	Low-Risk woodland + full restoration	Low-Risk woodland creation and the wild test scenario
	B5	Priority NFM + full restoration	Priority NFM woodland creation and the wild test parameterised scenario
	B6	Combined woodland + full restoration	All woodland recommended in the woodland feasibility report implemented on top of the wild Test in-channel intervention scenario.

5.3 Results

All NFM scenarios are compared to the baseline model run to ensure that changes measured are relative changes between model runs, and not measures of the absolute changes possible in the Test catchment. Scenarios A1-3 are river restoration scenarios and represent increasing river restoration coverage of the River Test network. Scenarios B1-3 represent the effect of implemented woodland areas identified as having potential for woodland creation in the Test catchment and scenarios B4-6 represent combining increased woodland creation with a re-vegetated river Test channel network, having implemented all of the river channel issues identified in the Test and Itchen River Restoration Strategy.

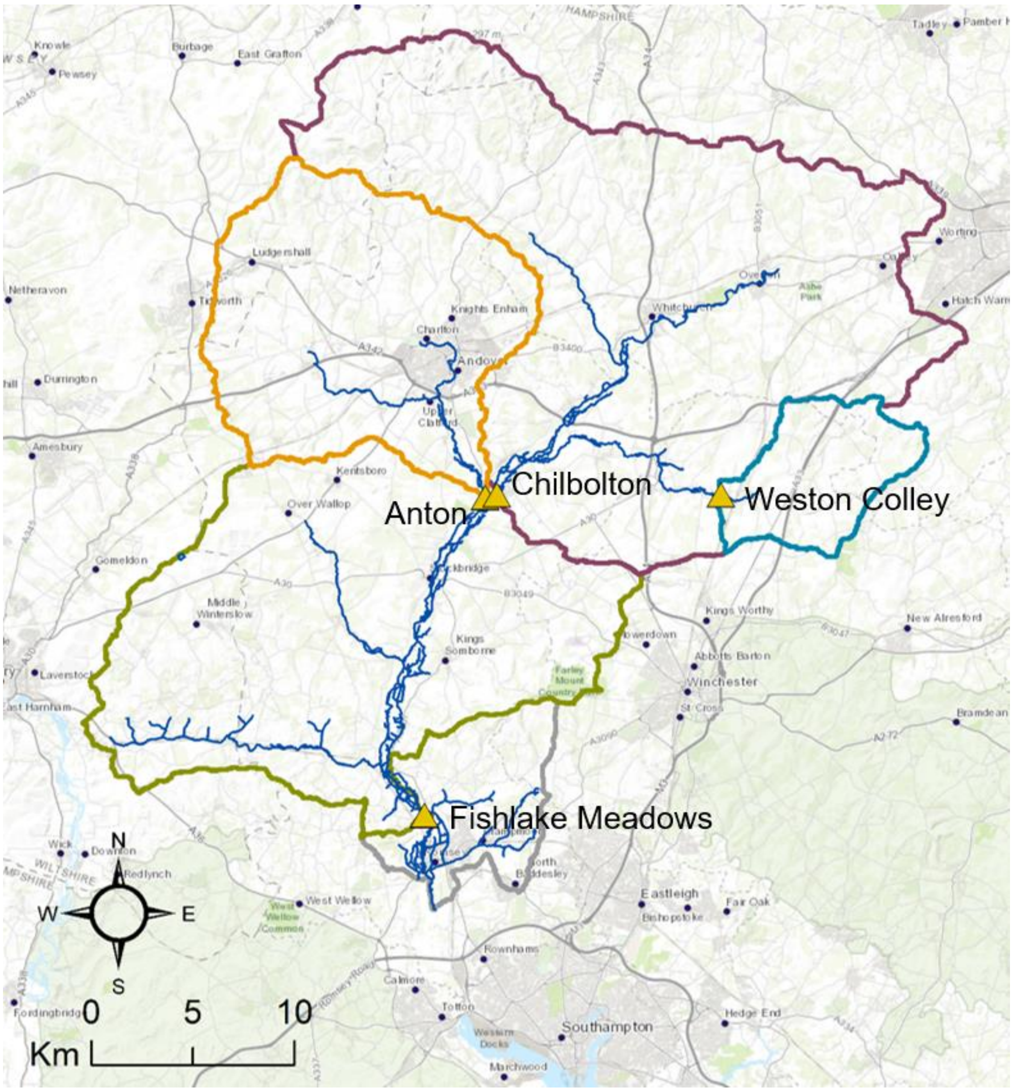


Figure 29 A catchment map of the River Test and the location of gauges used as flow outlets in the SHETRAN model. These gauges were chosen due to having good quality data and a long data record.

Table 18 The percentage coverage of deciduous woodland in each sub-catchment in the River Test for each woodland scenario.

	Fishlake Meadows	Anton	Chilbolton	Weston Colley
CEH LCM2007 Deciduous woodland cover	7.7%	3.2%	5.2%	13.2%
Low-Risk woodland deciduous woodland cover	25.0	15.7	23.8	46.1%
NFM priority deciduous woodland cover	9.5%	6.5%	7.7%	16.9
Combined NFM woodland cover	27.5	17.8	26.08	47%

Overall, the number of flood events stays relatively stable throughout all scenarios (Figure 31), keeping a constant average of 35, 11 and 9 for the Fishlake Meadows, Anton and Chilbolton respectively. There are small changes in flood incidence, but such small changes are thought to be due to the sensitivity of the flood metrics to small changes in discharge. For example, small changes in modelled water level due to increased or decreased discharge may cause a flood event of similar lengths to be broken into multiple floods due to flows being just below the overbank threshold for one (modelled) day, or flood events may be reduced similarly by two previously separate floods becoming merged in to one longer flood. The percentage of time that banks are overtopped stays much the same across the in-channel intervention scenarios, with larger reductions in overall bank overtopping being shown to be due to woodland creation (an average reduction of 0.15% bank overtopping from in-channel to woodland scenarios +/- 0.2%). Most notably, scenarios B1 (low risk woodland creation), B4 (Low risk woodland creation and the wild test in-channel intervention scenario) and B6 (combined woodland and the wild test in-channel intervention scenario) caused the greatest reduction in the percentage of time banks are overtopped with an average 2.8% bank overtopping for these scenarios compared to 3.1% for the baseline scenarios. This can be seen for all gauges but is most pronounced at the Anton gauge. Overall, it can be seen that in the woodland creation NFM scenarios, where the percentage of time banks are overtopped is reduced, it is reduced for all gauges in the Test catchment. This is not the case for the number of flood events, but this is thought to be due to defining flood events a day apart as separate flood events.

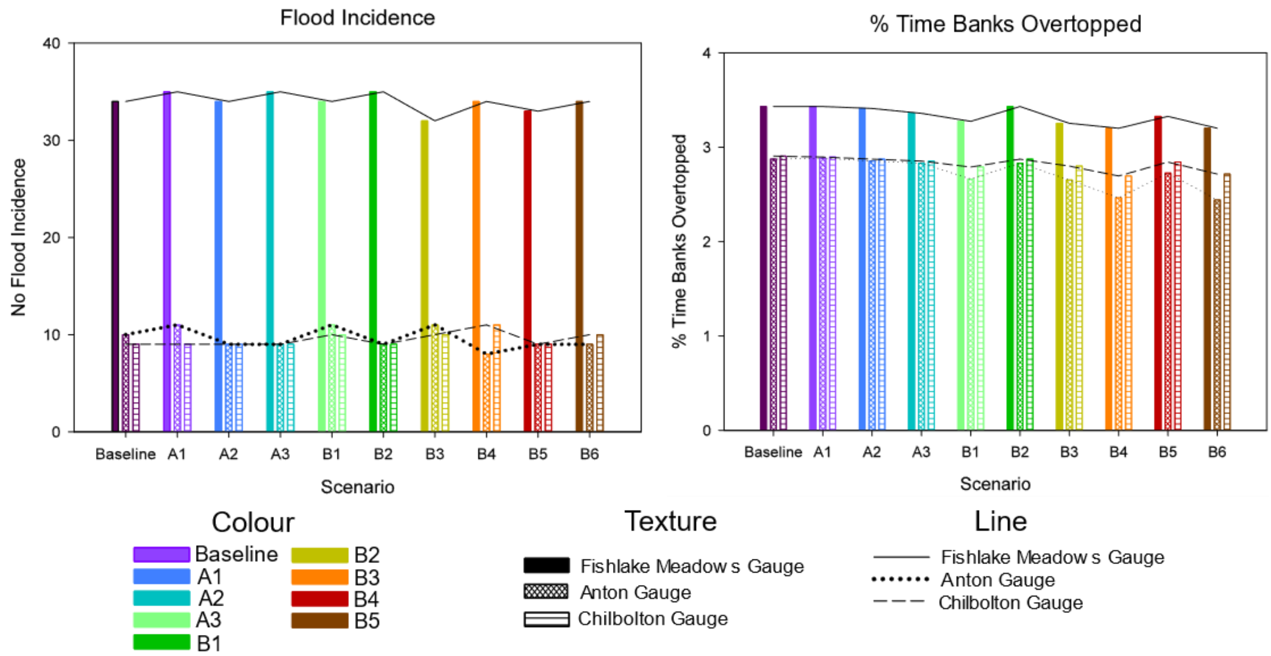


Figure 30 Bar charts showing changes to flood incidence (left) and the percentage of time banks are overtopped (right) in the Test catchment due to modelled river restoration and woodland creation scenarios.

At all gauges, the maximum flood duration is between 86-90 days (Figure 32) and is associated with the modelled 2014 flood event. The distribution of flood duration at all gauges is skewed to lower flood durations, with the majority of all floods occurring between 1-14 days. This is more difficult to discern at the Anton and Chilbolton gauges as there were fewer bank overtopping events (Figure 31). In general, in-channel interventions did not make large reductions to flood duration, particularly for maximum flood durations. Woodland creation for NFM generated 1-day reductions to maximum flood duration during scenarios B4 and B6 at Fishlake Meadows, and B3, B4 and B6 at the Chilbolton gauge. The greatest reductions to flood duration are at the Anton gauge, where increased NFM intervention at this site generated increased maximum flood duration reductions from scenarios B1-B6. This equates to a 5-day reduction in flood duration at the Anton outlet.

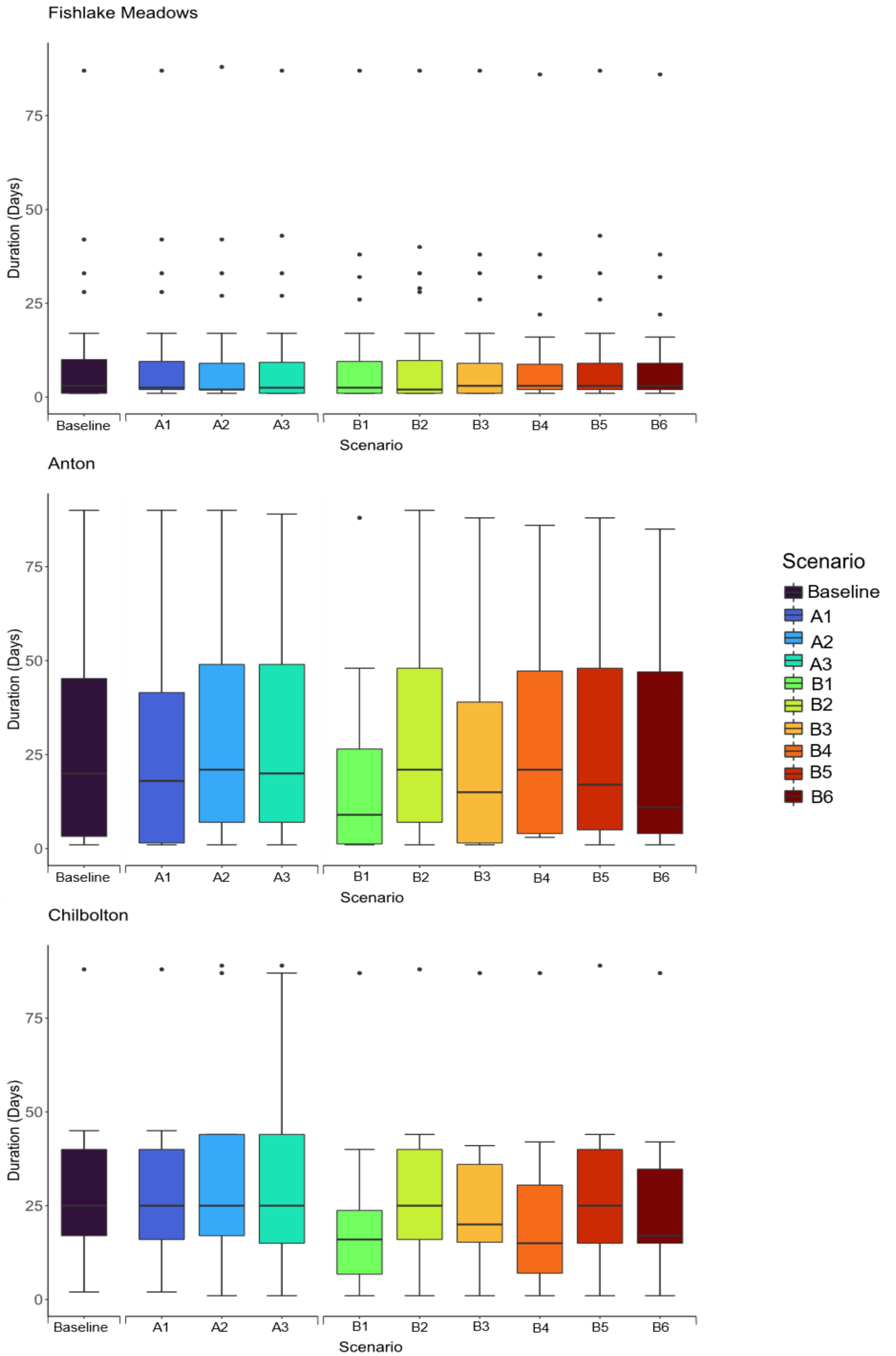


Figure 31 Box plots demonstrating changes to flood duration in the Test catchment at the Fishlake Meadows, Anton and Chilbolton gauges under river restoration (A scenarios) and increased woodland area (B scenarios) compared to the baseline scenario.

Flood peaks in the modelled Test catchment are reduced due to the implementation of NFM compared to the non-NFM baseline at all gauges, apart from Weston Colley where in-channel interventions cause a 2% increase in flood peak in the in-channel interventions. The general trend shown in the previous graphs is maintained, with in-channel interventions generating the smallest flood peak reductions, and woodland creation for NFM generating larger flood peak reductions at all gauges. Greater flood peak reductions are observed at both the Fishlake Meadows outlet and the Weston Colley outlet, with average flood peak reductions at the Anton and Chilbolton gauges being tightly clustered around 2% compared to the baseline. At both the Anton and Chilbolton gauge, the most effective NFM scenario is B6 (combined woodland and wild test river restoration scenario) with maximum flood peak reductions of 3% and 6% respectively and average flood peak reductions of 2.5% and 3% respectively.

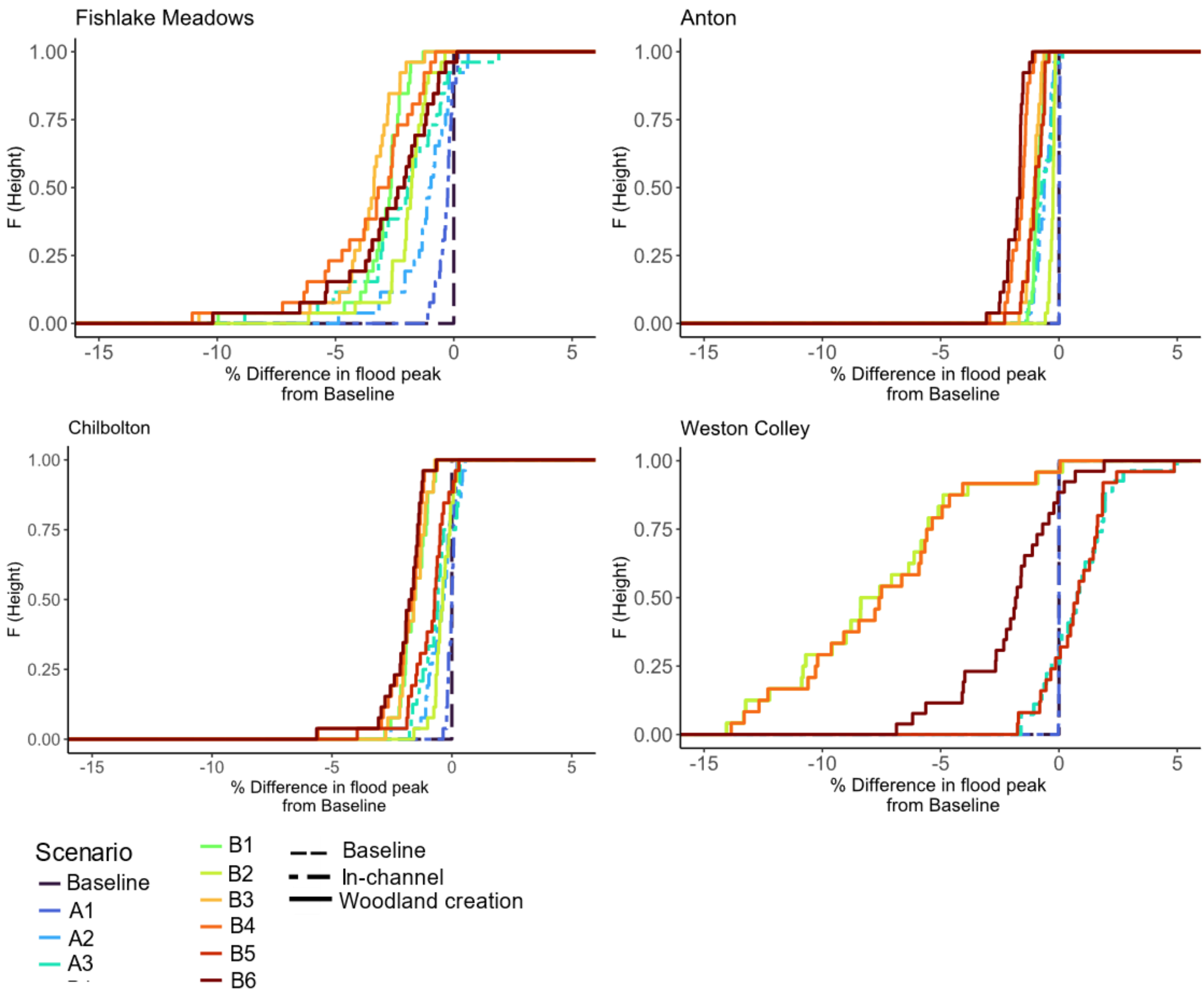


Figure 32 Estimated cumulative distribution function plots of percentage changes in flood peak compared to the baseline scenario due to river restoration (A scenarios) and increases in woodland area (B scenarios) for NFM in the Test catchment.

The greatest flood peak reductions are seen at the Fishlake Meadows and Weston Colley outlets with up to 12% and 14% reduction at each outlet, respectively. Both of these gauges show a greater spread of results depending on the NFM scenario. The most effective flood peak reduction scenarios at the Fishlake Meadows gauge are (in high to low order of average flood peak reduction) B3 – combined woodland creation, B4 – Low risk woodland creation with the wild test river restoration scenario, and B6 – combined woodland with wild test river restoration.

Weston Colley shows a large range in flood peak outcomes due to NFM implementation with some step changes and groups of scenarios. In-channel interventions increase flood peaks (up to 5%), woodland scenarios reduce flood peak (up to 14%) and combining woodland creation and in-channel interventions generates results in between. It is therefore thought that flood peak reductions caused by increasing woodland area being moderated by the flood peak increase caused by increased channel roughness, resulting in an overall average 2% flood peak reduction for scenario B6. At this gauge, the most successful scenarios are B2 and B3 (priority NFM woodland and combined woodland) with maximum flood peak reductions of approximately 14%.

The effect of woodland creation at each site is likely due to the proportion of woodland creation in each catchment. Weston Colley has a high proportion (47%) of the catchment converted to woodland, generating a greater impact at this site. Woodland creation is the most effective NFM intervention modelled in the Test catchment. Where combining woodland creation and in-channel interventions, spatial effectiveness needs to be considered (Dixon et al., 2019). These results suggest that the total effect is catchment dependent. Smaller catchments are more likely to experience increased flood peaks due to in-channel interventions, which needs to be taken into consideration during NFM design. Due to insufficient data to generate a rating curve at the Weston Colley site, in was not possible to ascertain the effect that increased flood peaks at Weston Colley due to in-channel interventions might have had on flood durations at this gauge.

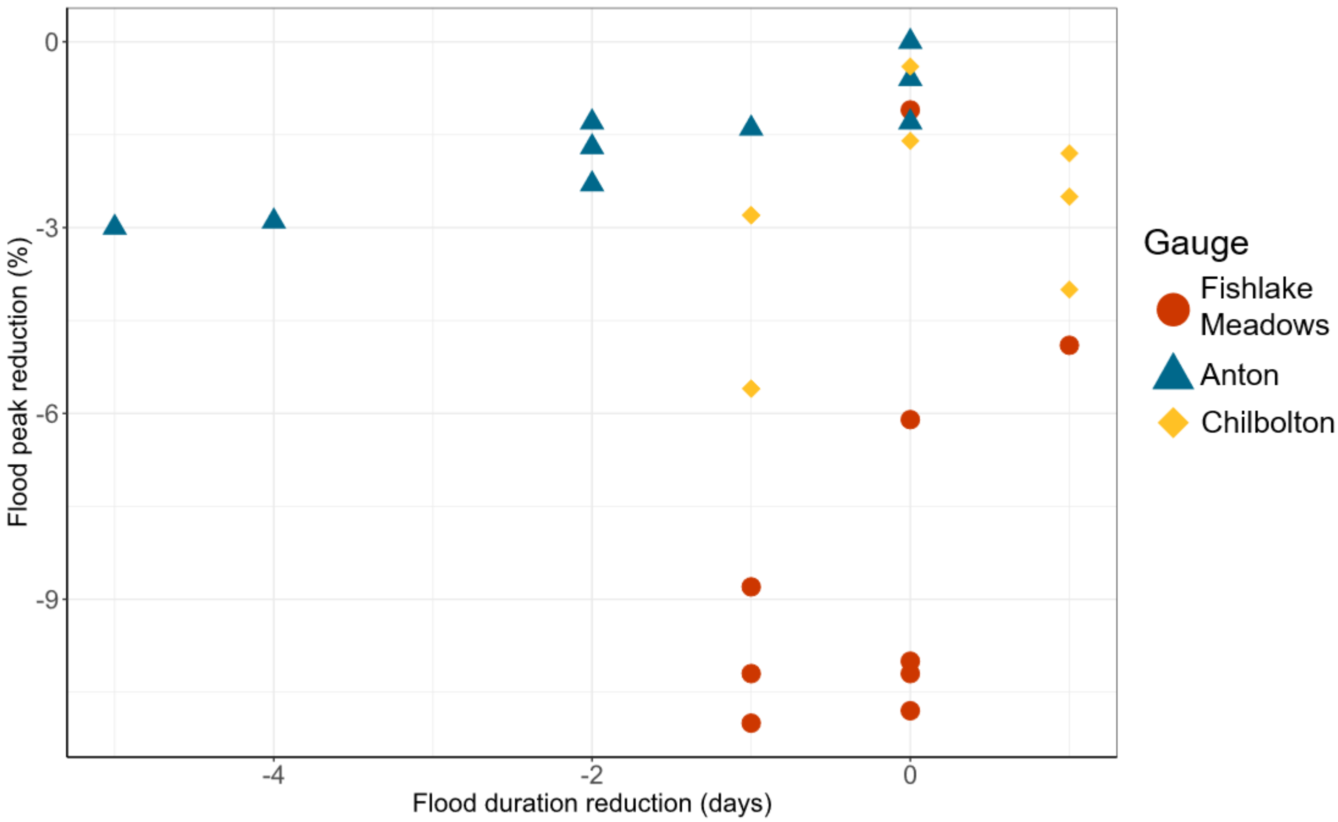


Figure 33 Maximum flood duration vs maximum % flood peak reduction for all gauges and all scenarios.

Figure 34 highlights the difference in catchment response to NFM at the different River Test sub catchments. The Fishlake Meadows gauge demonstrates the least response of any of the gauges but with some of the greatest peak flood reductions. The Chilbolton gauge demonstrates the least overall change due to NFM implementation, with very small reductions in flood duration and maximum flood peaks. The Anton gauge occupies the top left of the graph with relatively small maximum flood peaks reductions but higher potential flood duration reductions. The Anton gauge is the most sensitive to changes in water level height. This is also reflected in the rating curve and the uncertainty margins in the rating curve (Figure 23, section 4.2.2.1). On the contrary, the Fishlake Meadows gauge does not manifest reductions in flood peaks as an equivalent reduction in flood duration. Thus, the modelling study highlights that each gauge responds differently to combinations of NFM implementation.

5.4 Discussion

Reductions in flood peak have been observed relative to the pre-restoration baseline. For all gauges in the Test catchment, an average 5% peak flow reduction has been observed for combined increased tree cover and river restoration NFM scenarios, with a maximum of 14% peak flow reduction simulated for increased tree cover scenarios at the smallest Weston Colley gauge. A similar study by Adams et al. (2019) which used SHETRAN to simulate the effect of increasing forest cover to 40% and 50% of the catchment river network being affected by leaky barriers (represented via the Strickler flow resistance equation in SHETRAN the same as in this study) observed a 15% reduction in peak discharge. The test catchment in their study is of comparable size to the Weston Colley topographic catchment area which is 52 Km^2. This demonstrates that the average flood peak reduction is less than has been simulated in other similar studies, but the maximum flood peak reductions are comparable. Most other comparable NFM studies researching the impact of combining in-channel interventions and increasing tree cover observed flood peak reductions between 15% and 40% (median 25%) (Acreman et al., 2003; Huang et al., 2003; Iacob et al., 2017; Jackson et al., 2008; Quinn et al., 2013; Rosenqvist, 2007; Thomas & Nisbet, 2007). Therefore, within the context of the wider literature, a 5% reduction in flood peak (whilst positive), is much lower than has been observed or modelled in other runoff dominated catchments.

Small reductions in flood peaks can be used to maximum effect by increasing the resilience of other more utilitarian methods (such as hard engineering). Ferguson & Fenner (2020) found that simulated afforestation and LWD implementation sightly desynchronised rural and urban flood waves, reducing the water depth at drainage outfalls, preventing system capacity exceedance up to a 1% Annual Exceedance Probability flood (which was exceeded under a no-NFM scenario). This is likely applicable in this instance. Whilst the number of flood events is not significantly impacted by NFM implementation, the percentage of time banks are overtopped reduced from 3.1% to 2.7% from the baseline to B6 (combined woodland and channel rewilding) scenario respectively (Figures 30 and 32). Under these scenarios, the number of short duration floods reduced the number of 1-2 day-long floods and split some of the longer floods into two separate overtopping events (e.g., 7-day flow reduced to a 3- and 3-day flood with a day between them). Therefore, the number of flood incidence remains stable, but the constitution of flood durations changes very slightly. The effect is very subtle, but it suggests that marginal reductions in flood peaks may reduce bank overtopping for small-scale flood events. It is theorised that the reason this effect is so subtle is due to the buffering effect of the groundwater flood response. Due to generally thin soils and highly permeable chalk bedrock, the proportion of surface runoff in the river regime is reduced and floods are often caused by steady rises in the flow regime forced due to gaining hydrostatic pressure and baseflow inflows due to a rising water table after prolonged rainfall (Berrie, 1992a; Lamontagne et al., 2014; Wood et al., 2001). Groundwater dominance means that quick flow processes of flood generation contribute little to overall flooding (Sear et al., 1999) thus NFM has a limited effect as much of their process basis is aimed at reducing runoff (Lane, 2017). Similarly, the low ratio of flood height to bank full height in chalk streams results in limited reductions in flood duration. In summary, NFM techniques are unable to substantially influence the key source of flooding – namely recharge of chalk aquifers during periods of high rainfall over winter months (Mackay et al., 2015).

In the River Test catchment modelling scenarios, the larger flood peak reductions that have been simulated have not resulted in large reductions in flood duration (Figures 31 and 32). This is significant because of the nature of groundwater flooding. The buffering effect of a large sub-surface store of water generates a highly modulated and delayed flood response. Antecedent conditions play a major role in a catchment's sensitivity to rainfall and flood risk (Mackay et al., 2015). The weeks prior to a groundwater flood are often characterised by prolonged rainfall and saturated soils. This prolonged wetness allows for gradual recharge of aquifers as water inputs exceed water outputs. The water tables rise as the bedrock becomes saturated and the risk of groundwater-dominated flooding increases (McKenzie et al., 2010). Indeed, simulated flood peaks in this study were between 85-89 days long (Figures 31 and 32). Therefore, a maximum reduction of 4 days in the flood duration and an average of 1 day flood reduction is insufficient to reduce the potential disruption from groundwater dominated flooding in these catchments, despite the small reduction in flood peaks observed.

There is uncertainty associated with the flood duration estimates due to the uncertainty in the rating curves used to calculate the original flood thresholds. As shown in Table 14, the flood discharge threshold uncertainties are +/- 2.3, 0.1 and 0.4 m^3/s for the Fishlake Meadows Gauges, Anton and Chilbolton respectively. Using these ranges of thresholds, the variation in flood duration was calculated. Fishlake Meadows and Chilbolton have an uncertainty range of +/- 2 days flood duration and the Anton gauge is +/- 8 days. Consequently, all variations in flood duration in these NFM scenarios are within the range of uncertainty for all gauges on the River Test.

As is demonstrated in Figure 34, NFM implementation has varied impacts in terms of flood benefits at subcatchment. In this case, the smallest flood peaks, but greatest relative reductions in flood duration were observed at the Anton gauge (3% flood peak reduction and 5 day flood duration reduction +/-8 days), and the Fishlake Meadows gauge has the opposite effect with the greatest reductions in flood peaks (11% peak flood reduction) but the least change in flood duration (1 day +/-2 days). The Chilbolton gauge is observed to be the intermediate location, with modest reductions in both flood peak and flood duration (maximum flood peak reduction of 5.9% and flood duration reduction of 1 day +/-2 days). The Anton gauge is clearly highly sensitive to water level for bank overtopping events. This is evident because it has the smallest range in flood threshold uncertainty (+/- 0.1 m^3/s), yet has the greatest range in flood duration uncertainty, demonstrating that a small change in water level results in a greater variation in the time the flood threshold (or approximate bank full threshold) is exceeded. The Anton gauge also has the smallest flood peak reductions, but the greatest relative changes in flood duration. Because this area is so sensitive to changes in water table height, it may make it eligible for measures as described by Ferguson & Fenner (2020) where NFM is concentrated in the upper headwaters to slightly reduce water levels downstream. It may also make it a likely location for small embankments to maintain water within the channel and floodplain.

Woodland creation for NFM generates greater flood reduction benefits than in-channel river restoration measures, apart from at Weston Colley. River restoration and in-channel interventions have been found to deliver the best results as part of a suite of other NFM measures (DEFRA, 2004). This may explain why scenarios representing in-channel interventions and vegetated channels had limited flood reductions compared to scenarios B1-6. Aside from the Weston Colley gauge, reductions in flood duration appear to be linked to catchment size, with the greatest reductions in flood duration occurring in the smaller catchments (Figure 34). Generally, greater reductions in smaller catchments are expected because the literature demonstrates that the effects of NFM are drowned out in larger catchments (Dadson et al., 2017). Excluding Weston Colley, Fishlake Meadows has the greatest relative reduction in flood peak. This is thought to be due to the proximity of woodland creation opportunities to the gauge, the distribution of woodland throughout the catchment, as well as the proportion of the catchment wooded under the combined woodland scenario (Table 16). The Fishlake Meadows and Chilbolton gauges had a similar proportion of the catchment impacted by woodland creation under the combined woodland scenario, but Fishlake Meadows has much greater reductions in flood peak (maximum flood peak reduction of 11.5% and 9.8% respectively). This discrepancy could be due to the distribution of the woodland creation opportunities within these catchments. O'Connell (2008) found that woodland that is distributed throughout the catchment has a greater effect by causing continuous turbulent and transverse flows, causing a greater reduction in surface runoff velocity. To the point where when this is scaled up, more sparse woodland with a reduced canopy and basal area had a comparative flood mitigation effect to a scenario with a greater number of trees situated in a dense cluster (O'Connell, 2008). This disparity between Fishlake Meadows and Chilbolton is therefore believed to be due to the fact that woodland creation opportunities in the Chilbolton sub catchment are clustered in the lower part of the sub catchment, and woodland creation opportunities are distributed more evenly throughout the whole Test catchment.

The Weston colley subcatchment gauge demonstrates the greatest reductions in flood peak. The affect this has on flood duration, flood incidence and the percentage of time at bankfull cannot be calculated due to insifficient data to develop a rating curve and flood discharge threshold. The success in reducing the flood peak is thought to be due to woodland creation impacting the largest proportion of the catchment (47%). Previous studies have demonstrated that a large porportion (at least 20%) of a catchment can be required to be converted in to woodland to generate significant runoff storage to affect flood peak reductions (Huang et al., 2003). This is certainly the case in this instance, with nearly half of the catchment being converted to deciduous woodland under the combined woodland scenario. Additionally, woodland creation opportunities are more distributed throughout the catchment, rather than clustered in a specific area, enhancing the effect of tree planting (O Connell, 2008).

Unlike the other three catchments, in-channel NFM interventions did generate a large change in flood peak in the Weston Colley gauge. Peak discharge increases (up to 5%) for the in-channel scenarios (A1-A3). This is likely because the river channel is much smaller in the headwater catchments with far lower discharges than the other gauges, meaning that the relative effect of increasing manning's roughness values has a far greater retardant effect on conveyance in the river channel (Richards & Hollis, 1980). In the smaller channels, the height and volume is greater relative to the stage and discharge, meaning that the retarding and backwatering effect of vegetation and woody debris is greater (Watson, 1987), raising the water level and causing more bank overtopping due to in-channel interventions at the Weston Colley gauge rather than the other three gauges in the study. Scenarios B4-B6 show that reductions in peak flows from tree cover were moderated by the bank overtopping caused by the relative effect of increasing manning's roughness values in the Weston Colley sub catchment. The additional benefits of increasing tree cover in an area, aside from potential flood peak reductions include soil stabilisation, carbon sequestration, retention of nitrates in soils stopping them entering the river system, increased habitat and biodiversity, and the social, aesthetic, and mental health benefits of having forests available for recreation and scenic purposes (Balls et al., 1995; Burgess, 1999; Burton et al., 2018; England et al., 2020; Iacob et al., 2014).

Although statistical evidence in Chapter 3 suggested that river restoration and in-channel NFM interventions may be the most viable for chalk streams due to the lack of significant surface runoff processes, the modelled simulations demonstrate that minimal flood benefits can be gained using these methods in a Type 2 chalk catchment (Barnsley et al., 2021, Chapter 3). It is therefore likely a more productive allocation of resources to focus channel management efforts on the ecological requirements of chalk streams rather than attempting to effect flood reductions. The requirements and targets for river restoration on the River Test are well defined due to the Test and Itchen River Restoration strategy and focus on ecological benefits rather than NFM. This study confirms this as the appropriate rationale, whilst focussing NFM on woodland planting schemes.

One of the main barriers to implementing the NFM scenrios in the current study will be the requirement for space and land to convert to woodland and the differing requirements for channel and land management across the River Test catchment. Although all of the NFM scenarios in this suite of research were designed based on reports, reccommendations and opportunity mapping, it is unlikely that all of these recommendations can be carried out. This is already evident in the uptake of the recommendations of the Test & Itchen River Restoration Strategy which was published in 2013. Figure 19 (Section 4.3) demonstrates that whilst less intensive channel management has been promoted on the Rivers Test and Itchen in the last decade, vegetation management is undertaken by individual land owners with river management preferences influenced by commercial interests such as fisheries. The same can be said for the woodland creation in the River Test catchment, where actual uptake of afforestation schemes is likely to fall short of the original recommendations. The main barriers to implementing woodland creation and further river restoration efforts will likely be due to difficulties in securing funding and the requirement to establish agreements over who is subsequently responsible to maintain these NFM efforts (Bark et al., 2021; Wells et al., 2020). It is expected that this will be further complicated by the competing needs and interests of multiple stake holders (Newson et al., 2021). For this reason, it is unlikely that the full extent of the NFM implementation modelled in this study will be realised in application, further reducing the potential flood benefits realised by NFM implementation in such complex systems as the River Test and other similar chalk streams.

5.4.1 Conclusions

In summary, an average 5% peak flow reductions have been simulated at various sub-catchment scales across the River Test catchment, with a maximum peak flow reduction of 15% at the West Colley sub-catchment which is the smallest and most rural catchment in the study. These peak flow reductions are modest compared to other modelling studies in flashier surface water-dominant catchments. The reductions in peak flows in this study have similarly translated into small reductions of 1-2 days (on average) flood duration, which is within the range of uncertainty for the model. Since groundwater-dominated floods have long durations, and a large amount of disruption is caused by long durations, this lack of significant change in this area suggests that the NFM methods modelled may not reduce the overall severity of groundwater-dominated floods. The largest NFM effects are seen in the smallest catchment with the highest proportion of woodland restoration. However, due to a lack of available data, the impact of the 14% peak flow reduction on the flood duration in Weston Colley is unknown making it difficult to comment on the overall success of NFM schemes at this gauge. A limited flood reduction effect of in-channel NFM suggests that river restoration should be completed predominantly for the ecological benefits and for river restoration purposes. Afforestation has demonstrated some success in generating flood benefits in groundwater-dominated chalk catchments, but there are significant trade-offs as large quantities of land are required to be converted to woodland to generate these changes. Whilst all of these scenarios have been designed based on previous recommendations and opportunity maps, the main barrier to uptake is often find funding pathways and allocating responsibility for maintenance and upkeep. Therefore, highly permeable chalk catchments such as the River Test (Barnsley et al., 2021) are unlikely to benefit from existing NFM measures implemented at a scale that is realistic based on competing interests.

Chapter 6 The resilience of NFM interventions on the River Test to climate change

6.1 Introduction

It is well established that future projected climate changes are likely to lead to a warmer climate and increased flood risk globally (Hirabayashi et al., 2013; Shukla et al., 2019). The most recent local-scale climate projections for the South Coast of the UK, published in 2018 (UKPC18), predict a 20-30% increase in winter rainfall and the same decrease in summer rainfall by the end of the century (Lowe et al., 2019). Under these projected conditions, there will be a marked increase in prolonged heavy winter rainfall, and in the summer a greater risk of drought combined with increasingly severe short sharp convective rain storms (Lowe et al., 2019). The Natural Flood Management (NFM) evidence base so far suggests that more intense storms and prolonged wet conditions lower the effectiveness of NFM interventions as these measures become overwhelmed (Dadson et al., 2017). Most NFM studies only monitor NFM measures over a short to medium timescale after schemes are completed, so the longevity of NFM over time is relatively unknown (Murgatroyd & Dadson, 2019). This has led to major uncertainty about the resilience and benefits of NFM schemes beyond the near future (i.e., 10 years) and their usefulness under future climate change scenarios.

This chapter uses SHETRAN, a physically based spatially distributed model, and the NFM scenario designs detailed previously in Chapter 5 to assess simulated flow outputs under different climate change scenarios. NFM scenarios are compared against a non-NFM scenario to differentiate the relative simulated benefits of NFM implementation in more extreme conditions in the future. The UK Climate Change Projections 2018 (UKCP18) climate datasets are used to generate a new gridded rainfall dataset which is fed in to the SHETRAN model, driving climate change simulation in this study. The results are analysed and discussed to understand the potential policy implications of these modelled outcomes.

6.2 Methods

To generate climate change scenarios in SHETRAN, the scope of the analysis and the model requirements needed to be assessed against the available UK climate change data. As outlined in Chapter 5, this version of the SEHTRAN model requires spatially variable rainfall data, with a time series representing each 1 km^2 grid square. Therefore, climate change data must be spatially variable and representative of the South Coast of England where the River Test is located. It must also be in a spatial resolution that is fine enough for a relatively small catchment (1040 km^2 in total) and sub-catchments (Weston Colley is 52 km^2).

Among the most well know UK climate change dataset is the UKCP18 report. The UKCP18 provides probabilistic global climate projections over land up to the year 2100 globally at a 60 km scale and for the UK at 12 km and 2.2 km. Climate projections at the 12 km and 2.2km resolutions allows for more realistic simulation of convectional rainfall and climate activity related to topographic changes which were not present in previous iterations of the UK climate projections. The UKCP18 offers a direct upgrade from the UKCP09. The improvements include (Lowe et al., 2019):

- simulations of inter-annual climate variations due to the inclusion of models from the most recent Intergovernmental Panel on Climate Change 5 (IPCC5, 2013) climate models.
- a more comprehensive sampling of earth system modelling uncertainties,
- new metrics accounting for ocean heat uptake,
- new methodological statistical approaches,
- a global model which makes it easier to assess global issues which might affect the UK, such as food availability and storm tracks, for better weather modelling capabilities.

Generating UKCP18 climate models involved using many different variations of the Hadley Centre Coupled Model version 3 and other climate models to produce a range of simulated climate outcomes. A statistical emulator (which is what has been updated from the UKCP09) is then used to provide outcomes for a wide range of models which are then compared to observed climate data and weighted using a Bayesian statistical process according to their accuracy (Lowe et al., 2019). These weighted climate scenarios are then used to develop future scenarios called Representative Concentration Pathways (RCPs) which go from RCP2.6 up to RCP8.5. RCPs are designed to represent a more up to date range of assumptions about future population, economic development, and developments in technologies for greenhouse gas mitigation. RCP2.6 expresses a future of radiative forcing of 2.6 watts per meter square and represents a scenario where the global community successfully implement sizeable reductions in greenhouse gas emissions from 2018 onwards. In this scenario, there is a probability that global average warming is limited to 2 °C above pre-industrial levels, which is consistent with the UK target under the UK Climate Change Act. The most extreme scenario, RCP8.5, represents radiative forcing of 8.5 watts per meter squared and assumes that greenhouse gas emissions continue to rise after no changes were made by the global community to lower carbon emissions (i.e., the no mitigation scenario). Needless to say, the potential temperature increases under this scenario are much higher than under the RCP2.6 scenario, but the uncertainty range is too high to provide a precise estimate (Lowe et al., 2019).

The UKCP18 data is available as gridded rainfall estimates, as well as all other variables required to calculate Potential Evapotranspiration. However, the 2.2 km^2 gridded rainfall dataset is only available for the RCP8.5 scenario, the most extreme, which was not thought to be a fair analysis without a mitigated scenario to compare against. The 12 km^2 dataset is available for both the RCP2.6 and RCP8.5 scenario but was considered too coarse a resolution for accurately representing changes within the smaller sub-catchments. Additionally, these datasets would require spatial resampling, bias correcting and converting into appropriate formats for input in to the SHETRAN model which is a highly skilled and time-consuming process. As a result, the UKCP 18 probabilistic projection for the 2.2 km^2 dataset (rather than the raw datasets) were used for the 10^{th}, 50^{th}, and 90^{th} percentile for the RCP2.6 and RCP8.5 climate scenarios. The probabilistic projections estimate a percentage change in rainfall and land surface temperature based on support from the climate models and observed data. The 10^{th} to 90^{th} percentile projections are used because there is much stronger evidence for outcomes within this range than those found at the tails of the distribution (Lowe et al., 2019). These projections are provided in 20-year durations between 2041-2060 and 2080-2099. The nearest future scenario out of these two was used because it represents a more conservative climate change scenario. If NFM schemes become redundant under these conditions, it can be reasonably concluded that they will not be effective under the more extreme 2080-2099 scenarios. The UKCP18 2.2 km^2 resolution map of probabilistic futures from the UKCP 18 report was used to gain the projected percentage change in precipitation under the RCP2.6 and RCP8.5 scenarios for the River Test catchment (Table 17). These projected percentage changes were multiplied by the gridded rainfall times series from the CEH GEAR dataset used previously in the model setup in Chapter 5. This generates a new gridded rainfall dataset for each scenario with more extremes in rainfall and greater seasonal variations. This is a highly simplified version of the approach taken by the Water Resources South East datasets (Blair & Gough, 2020) which multiplied observed rainfall data by monthly forcing coefficients. This method also ensures that the results from Chapters 5 and 6 can be directly compared because they both use the same rainfall datasets.

Table 19 Probabilistic climate change projections for the River Test catchment for RCP2.6 and RCP8.5 for the years 2041-2060 (Lowe et al., 2019).

	Winter Precipitation change (%)			Summer Precipitation Change (%)		
	10th	50th	90th	10th	50th	90th
RCP2.6	-5	5	16	-24	-11	1
RCP8.5	-5	7	21	-31	-15	0

6.2.1 Finding seasonal transition points

A seasonal transition point was required to be able to interpolate the climate change projection values for summer and winter to avoid step changes in the new rainfall dataset. Daily average rainfall values for each day in the Julian calendar were subjected to change point detection in R statistical software using a Pruned Exact Linear Time (PELT) method (Killick et al., 2012). To achieve this, an elbow plot was generated using multiple different penalty parameters. The penalty parameter chosen was 8 (Figure 35) because this is where the elbow plot levels out, allowing confidence in change points detected using this parameter (Killick et al., 2012). Next, daily average rainfall values were subjected to a change point detection using the 'cpt.mean' function in the

'Changepoint' package in R which identifies changes in the data mean (Killick et al., 2012). Change points were detected on days 45 and 270 Julian day for spring and autumn transitions respectively.

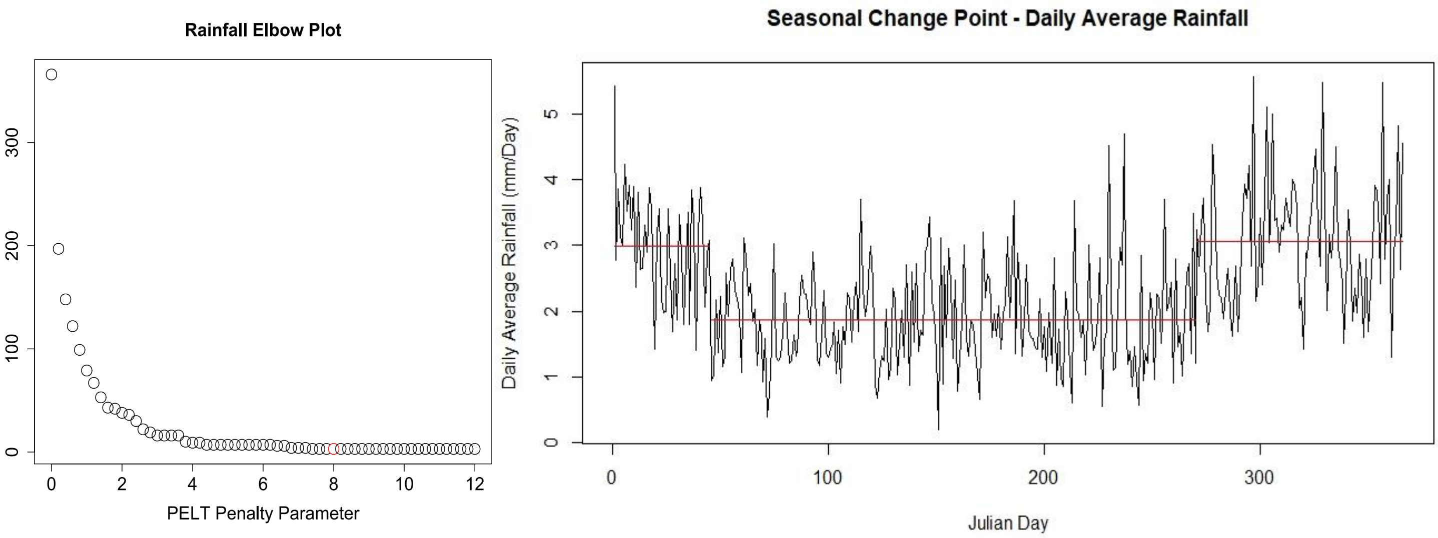


Figure 34 The seasonal transition point was detected for the daily average rainfall for all grid squares in the SHETRAN model (right) using the 'Changepoint' package in R. The elbow plot (left) was used to select the tolerance threshold for this measure. The value of 8 was selected because it is at this point that the elbow plot levels out.

6.2.1.1 Interpolating seasonal changes in climate projection

Via visual inspection of the daily average rainfall of the rainfall data, it was established that the seasonal transition period is roughly +/-25 days from the transition point identified via change point detection. Therefore, seasonal transition was found to be roughly 50 days in the autumn and spring. The change in percentage rainfall was therefore divided between this 50-day transition period to generate an interpolated percentage change dataset (Figure 36). This was then multiplied by the CEH GEAR gridded rainfall data used originally in Chapter 5 to generate a climate change rainfall dataset which was then used in the SHETRAN model.

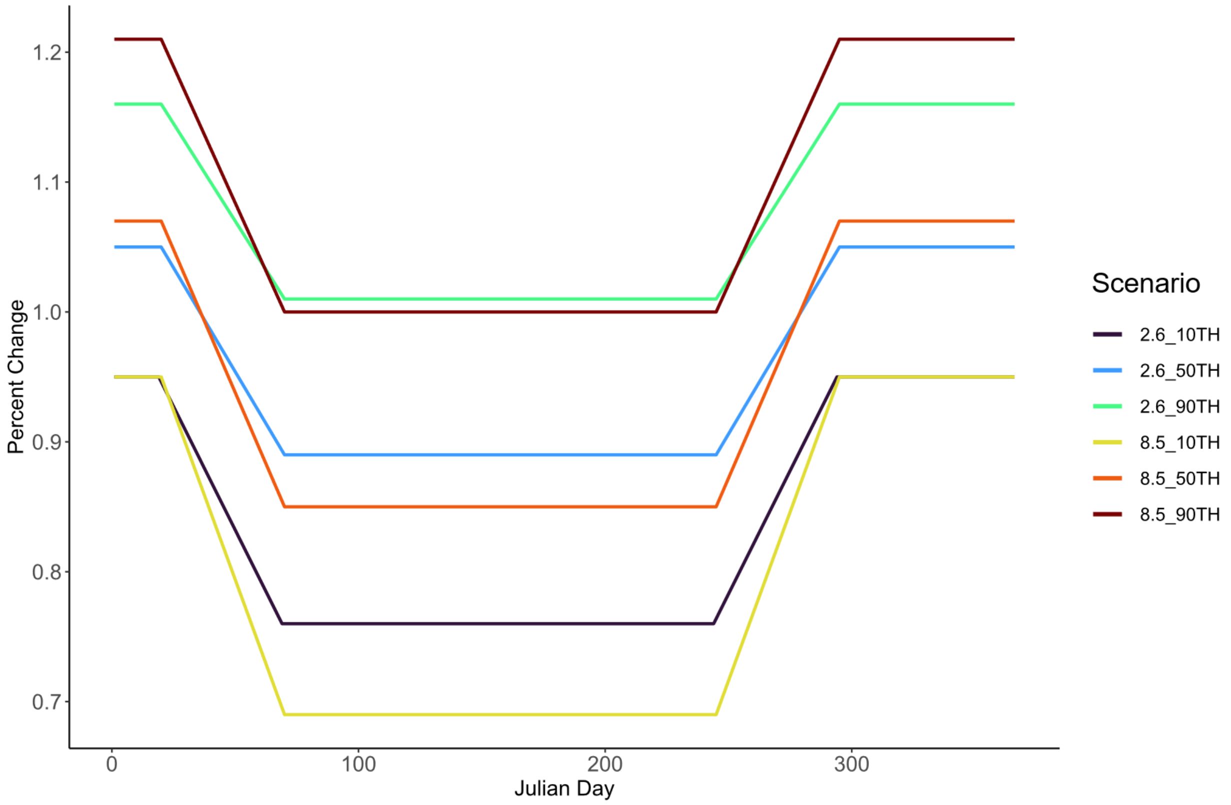


Figure 35 Percentages that the original rainfall time series are multiplied by to generate the new 'climate change' rainfall input datasets. This figure shows interpolation between change points avoiding unrepresentative step changes in the new rainfall inputs.

For model runs, the combined woodland and full channel restoration scenario (B6, Table 15) was used for each climate change scenario. This scenario was used because it represents the greatest area of NFM intervention as a proportion of the Test catchment. Each NFM scenario was compared against the baseline pre-restoration Test scenario for all of the new climate change rainfall datasets.

6.2.2 Climate change scenario matrix

Table 20 Climate change scenario summaries

Climate change scenario	**Percentile probability**	**Parameters**
RCP2.6	10^{th}	Combined woodland + full restoration plan
	50^{th}	Combined woodland + full restoration plan

	90th	Combined woodland + full restoration plan
RCP 8.5	10th	Combined woodland + full restoration plan
	50th	Combined woodland + full restoration plan
	90th	Combined woodland + full restoration plan

6.3 Results

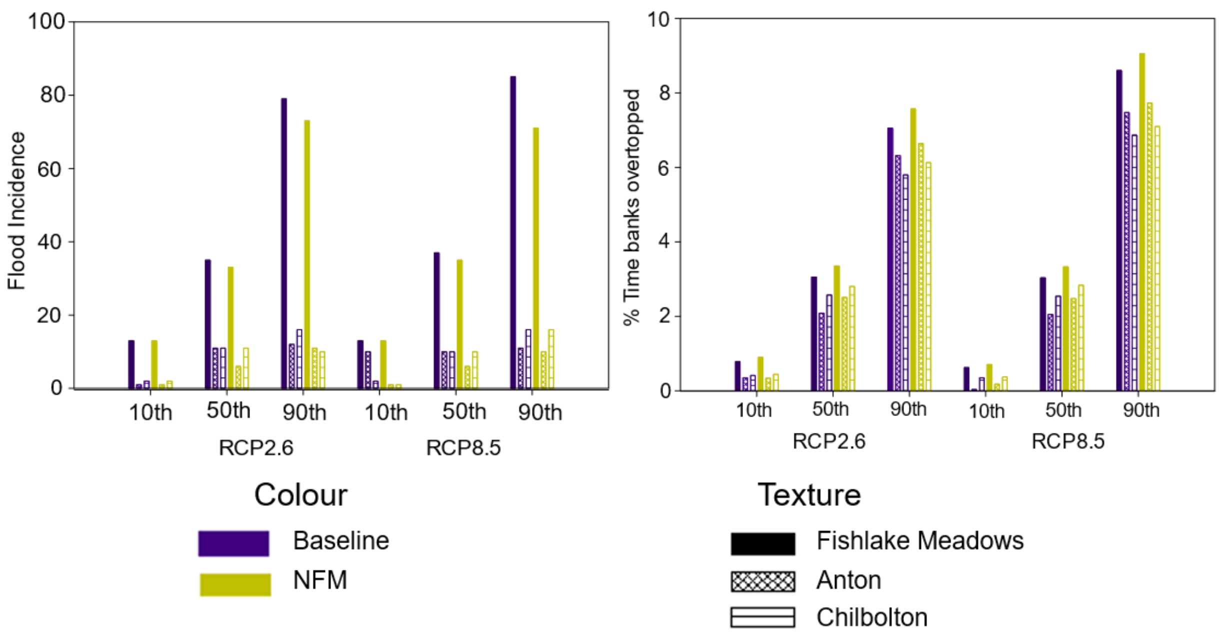


Figure 36 Flood incidence and the percentage of time banks are overtopped for RCP2.6 and RCP8.5 with 10th, 50th, and 90th percentile climate change scenarios under baseline and NFM conditions. NFM conditions constitute the full restoration plan in-channel interventions plus the combined woodland NFM scenario.

Generally, this suite of results demonstrates that the average flood peak reductions of approximately 5% compared to the baseline (Figure 40) are maintained through all climate change scenarios, and maximum flood duration reductions of approximately 2-3 days are also maintained (Figure 38) under climate change projected rainfall. Additionally, the sub-catchment trends were maintained, meaning that the Anton sub-catchment gauge maintained the greatest reductions in maximum flood duration (6 days).

In Figure 37, increases in flood incidence and percentage time banks are overtopped are thought to be due to percentile probability. NFM shows increased flood incidence reduction at higher percentiles, with a reduction of 11 floods at the 90^{th} percentile of RCP8.5 and 7 at the 90^{th} percentile of RCP2.6. However, this is not reflected in the percentage of time banks are overtopped. This is likely due to multiple shorter duration floods combining into a smaller number of longer duration floods under increased simulated rainfall. Figure 37 shows that the percentage of time banks are overtopped increases slightly for both RCP2.6 and RCP8.5 for the 50^{th} and 90^{th} percentiles in the NFM scenario compared to the non-NFM baseline.

NFM is most effective at reducing flood duration at the 10^{th} percentiles for all three gauges for RCP2.6 and RCP8.5 climate change scenarios (Figures 36 and 37), which represent the most conservative climate change probability (representing a reduction in winter rainfall and increased possibility of drought). Floods are predicted to increase in flood duration due to climate change, generating maximum flood durations of up to 180 days for the 90^{th} percentile of RCP8.5 at the downstream Fishlake Meadows gauge (Figure 39). At the Fishlake Meadows and Chilbolton gauges, NFM generates minimal flood duration reductions (0-2 days) (Figure 38). The greatest reductions in flood duration due to NFM implementation are found at the Anton sub-catchment, but it also has the greatest uncertainty range. Therefore, although there were some reductions in flood duration measured at this gauge, they are within the range of uncertainty for the flood threshold. This applies to all flood duration changes for these climate change scenarios.

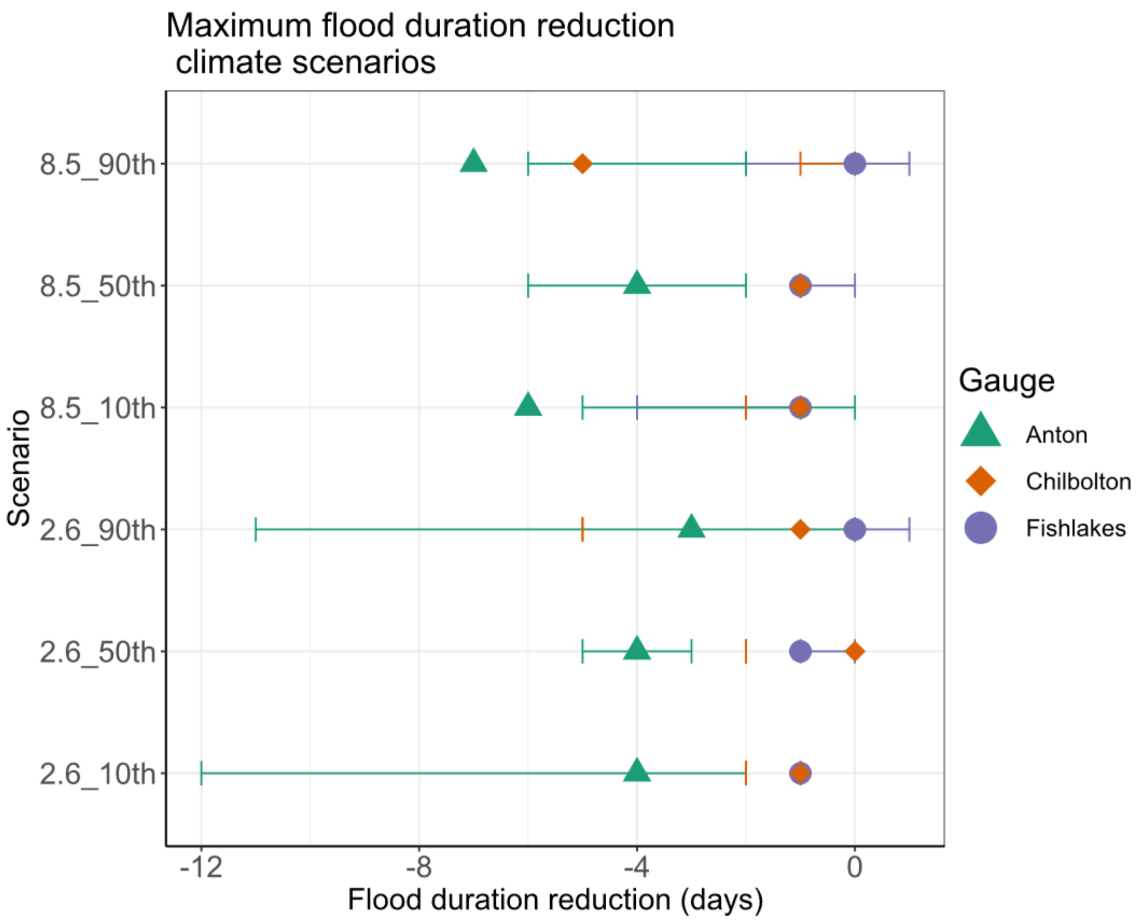


Figure 37 Maximum flood peak reductions at the Fishlake Meadows, Anton and Chilbolton gauges when comparing the combined woodland and river restoration NFM scenario with the non-NFM baseline for RCP2.6 and RCP8.5 with 10th, 50th, and 90th percentiles.

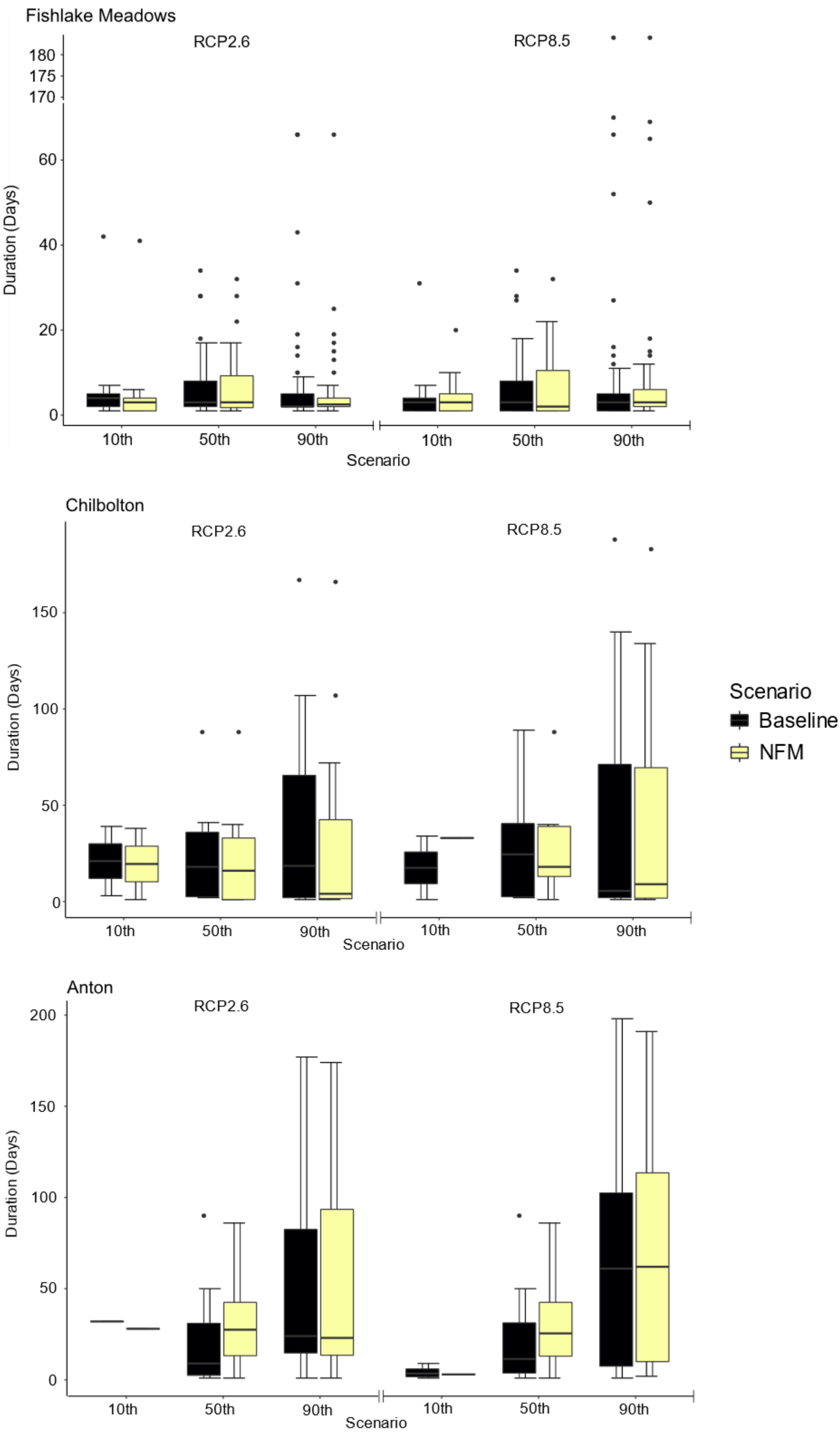


Figure 38 Flood duration for RCP2.6 and RCP8.5 with 10th, 50th, and 90th percentile climate change scenarios for the non-NFM baseline and the NFM scenario.

Flood peak reductions compared to the non-NFM baseline scenario demonstrate that flood benefits are maintained during future climate change projections, averaging around 5% for all gauges at both RCP2.6 and RCP8.5. These averages are grouped tightly between percentiles for both scenarios. There is a greater range in potential flood peak reductions for RCP8.5 at the Fishlake Meadows and Weston Colley gauges, most likely due to there being greater flow variability at these gauges.

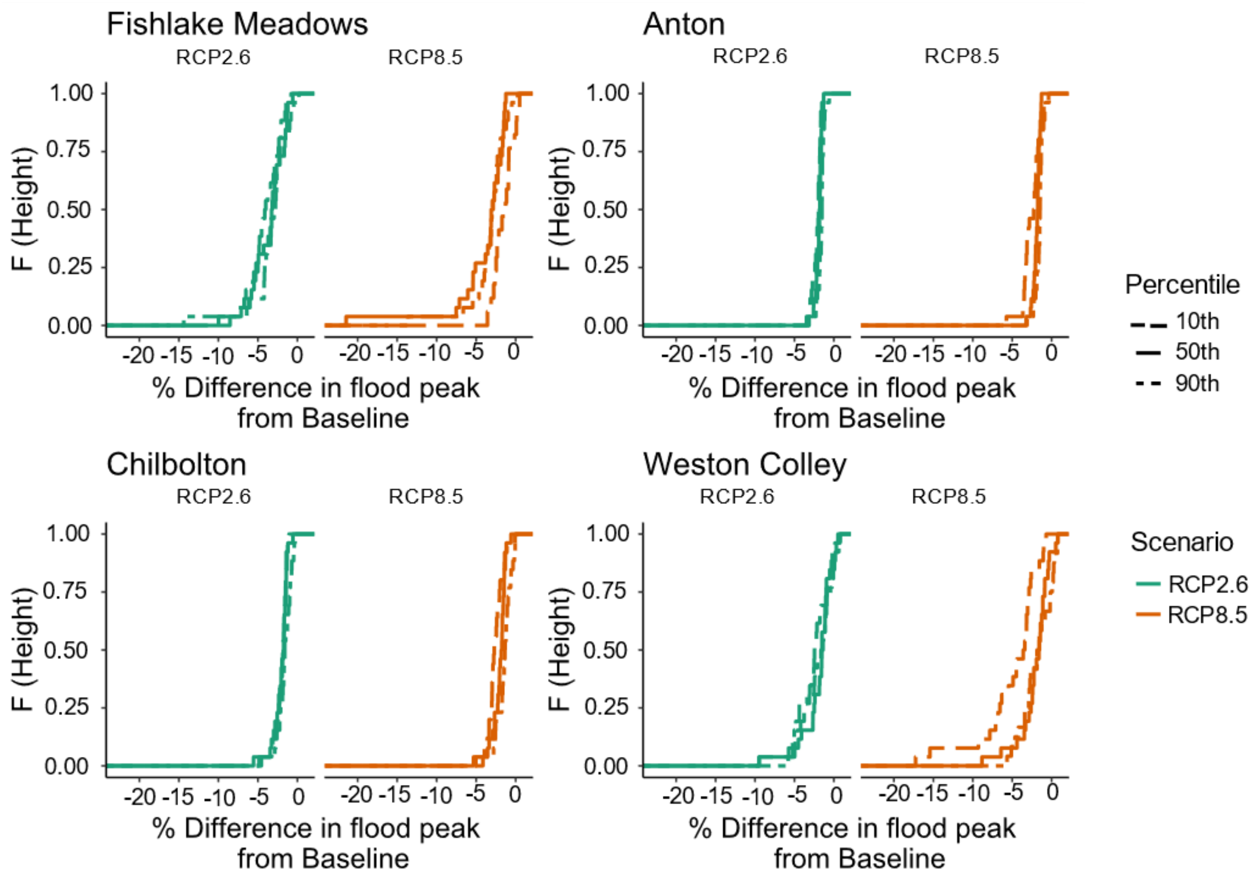


Figure 39 Cumulative distribution function plots displaying the flood peak reductions for NFM implementation compared to the baseline for RCP2.6 and RCP8.5 climate change scenarios with 10th, 50th, and 90th percentiles.

6.4 Discussion of climate change analysis

This set of results shows that the flood peak reductions compared to the non-NFM baseline remains roughly the same as observed in the woodland and in-channel NFM scenarios from Chapter 5, with an average 5% flood peak reduction and greatest flood peak reductions at the Weston Colley gauge (17% for the 10th percentile of RCP8.5). This is true for all RCPs and percentiles, including the most extreme 90th percentile scenarios which represent a 16% and 21% increase in winter rainfall for RCP2.6 and RCP8.5 respectively. Many other NFM studies have shown that higher intensity storms or higher magnitude events drown out the effect of the NFM measures and reduce their influence (Dadson et al., 2017; Ferguson & Fenner, 2020; Iacob et al., 2017; Murgatroyd & Dadson, 2019). It is most often found that there is a rainfall intensity scale effect, with the most NFM benefits found at lower intensity and magnitude flow events and the least benefits measured for more intense and higher magnitude storms (Kay et al., 2019; Norbury et al., 2021). However, despite the scale effect of storm magnitude measured in other studies, (Norbury et al., 2021) observed a peak flow reduction of 5% throughout the extreme 2020 storms Ciara and Dennis in the UK from a network of engineered leaky barriers. These observed results from Norbury et al. (2021) indicate that it is possible to maintain moderate flood peak reductions from NFM throughout intense storms, which is in the order of magnitude of the flood peak reductions simulated in this study. The lack of event scale effect observed in the results in this study could be due to the method used to generate climate change rainfall data. A generic increase of a percentage of winter rainfall may not adequately represent the increase in variance of rainfall and the potential intensity of storms in the projected future.

Figure 39 shows that the difference in flood duration also remains roughly the same as was observed in Chapter 5. Flood duration reductions range between 0-6 days, with the greatest flood duration reductions observed at the Anton gauge. All flood duration reductions are within the range of uncertainty and therefore cannot be used to generate flood peak reduction. Additionally, these reductions in flood duration are insufficient to generate a positive effect when compared to the simulated length of some of the floods under future scenarios. Prolonged rainfall during the winter months has led to simulated bank exceedance simulated for nearly 200 days for the 90th percentile in the RCP8.5 climate change scenario (Figure 39). At the more moderate 50th percentile for both RCP2.6 and RCP8.5, flood durations are predicted to increase to floods that are 89-95 days long (this in an increase from the maximum 88 days simulated in Chapter 5). This indicates that, despite maintaining a small flood peak reduction compared to a non-NFM baseline, this could be severely deficient to reduce flooding in groundwater-dominated catchments within the next 60 to 80 years under the UKCP18 projections. Clearly NFM solutions alone are inadequate, meaning that other hard-engineering solutions may need to be considered. An integrated approach of NFM and hard engineering has been advocated for as a favourable climate change adaptation strategy (Ferguson & Fenner, 2020). Evidence suggests that the environmental and ecological stability, as well as sediment capturing and flood peak reductions generated by NFM schemes, can increase the resilience of hard engineering structures such as levees and urban drainage during higher intensity storms (Ferguson & Fenner, 2020; Iacob et al., 2014). The River Test catchment, a chalk lowland stream, is highly sensitive to water level fluctuation. This means that relatively small raises in bank height could significantly reduce bank overtopping. For example, the difference between the flood threshold stage and the flood stage for the peak flood in the RCP8.5 90^{th} percentile simulation is only 32 cm. However, raising bank height would need to be applied with extreme caution as floodplain and wetland area flooding from chalk streams are important for maintaining ecological diversity and chalk stream specific species found in these areas which contribute to the SSSI status of some of the riparian sections of the River Test (Visser et al., 2019). Raising bank heights even a small amount may disrupt bank overtopping processes which are crucial to maintaining wetland ecosystems.

It must also be considered that projected climate changes in the South East of England are more often associated with stress on public water supplies and low flows due to prolonged droughts during drier months between April and September and greater variations in high winter flows and low summer flows (Herrera-Pantoja & Hiscock, 2007). Chalk streams have been shown to have a very limited ecological adaptation ability to climate changes. In their study Visser et al. (2019) found that despite increased annual variability, interannual hydrogeological response became increasingly homogenous under high emissions climate change scenarios. Similar interannual flow patterns (with very high winter flows and very low summer flows) over time will favour groups of plant and aquatic animal species which are best adapted to these conditions, narrowing chalk stream biodiversity and weakening the ecological resilience of the chalk stream environment (Visser et al., 2019). Greater annual variation in flows means prolonged periods of low flows and droughts putting pressure on the public water supply. This can be highly problematic because the chalk aquifer accounts for 80% of public water supply in the South East of England (Lapworth & Gooddy, 2006). Reduced aquifer recharge can also causes issues with nitrate pollution as relatively static aquifers become polluted with condensed agricultural nitrates which are then flushed out in to the river system during rapid recharge events (Whitehead et al., 2006). This raises real concerns about seasonal pollution in the chalk stream river systems. Therefore, the climate change concerns in chalk streams are primarily associated with ecological degradation and increased dry and wet season variability (Herrera-Pantoja & Hiscock, 2007; Visser et al., 2019; Whitehead et al., 2006). This is important because woodland creation has been a key component of NFM in this study, but converting large areas of land to woodland have also been found to exacerbate low flows in river systems (Iacob et al., 2017) However, there is some evidence that this effect is moderated in groundwater-dominated chalk catchments (Roberts & Rosier, 2005). Accordingly, further research would be required before the confident application of increasing the area of tree coverage to assess the benefits of flooding against the potential risks during drought under present and future climate projections. Furthermore, nitrate pollution in aquifers and the river network may become a highly pressing issue in the future and may need to be prioritised over the relatively small flood benefits that can be achieved through increasing the area of deciduous tree cover and in-channel NFM measures in chalk catchments like the River Test under future climate projections.

6.4.1 Conclusion

In summary, moderate reductions in peak flow (average 5%) are maintained for all, including the most extreme, climate projections compared to a non-NFM scenario. This demonstrated that a significant increase in tree coverage and river channel restoration and rewilding could maintain moderate benefits under all UKCP18 climate scenarios up to the next 80 years. These modest peak flow reductions do not translate into reductions in flood duration that are measurable beyond the range of uncertainty. This is a major shortfall for NFM function in the future, as future climate scenarios demonstrate extremely long flood durations for both RCP2.6 and RCP8.5 at the 90th percentile probability, suggesting that moderate peak flow reductions are insufficient to reduce major disruptions that would be caused by these simulated floods. These small benefits could be used as an adaptation strategy to support the resilience of other hard engineering approaches to flood management that may be required in the future. Because the benefits of NFM are mild, other future climate change pressures on chalk streams, such as seasonal nitrate pollution, pressure on the public water supply, and ecological homogenisation due to increased variation in the annual flow regime may take priority for the investment required for climate change adaptation strategies.

Chapter 7 Limitations and future research

Whilst this is among the first detailed studies of implementing Natural Flood Management in groundwater-dominated river catchment systems, a comprehensive knowledge gap still exists in the NFM evidence base. This chapter is aimed at addressing this and makes recommendations for the direction of future research based on the limitations of this study.

This suite of research has not addressed the potential of the use of NFM to directly intercept known intermittent sources of surface runoff. This is among the most pressing knowledge gaps of the current understanding of NFM application in chalk catchments. This refers specifically to sources of flowing water that activate when water tables are high, such as springs and winterbournes (Berrie, 1992; Furse, 1977). These hydrogeological features, which are unique to the chalk stream environment, are only active when water tables are high and can be a source of significant flood flows and increased flood risk (Hughes et al., 2011). Furthermore, it is known that there is currently interest from decision makers to understand the potential for implementing NFM measures to intercept these sources of water in the Test and Itchen catchments. Although NFM features implemented to intercept runoff from these intermittent sources of surface water would be redundant the majority of the time, they may contribute to slowing the conveyance of water downstream or intercept a considerable source of streamflow before it reaches the main river channel when flood risk is highest.

Mapping of hydrogeological features and groundwater emergence for standard use by decision makers and researchers could be greatly improved. Such maps were a requirement from the European Union Floods Directive (Cobby et al., 2009) and many attempts have been made previously to generate predicative groundwater emergence maps for planning, flood risk, and hazard mapping. So far, the methods to achieve this have been varied. Morris et al. (2007) included all karstic aquifers in the UK to gather data of flood extents from the 2000-1 winter flood event and proposed this as a first provisional step in developing groundwater flood risk maps. Other studies have used a combination of detailed geological maps, topographic data, and flood frequency assessments to try to develop hazard maps for groundwater flooding (McKenzie et al., 2010; Najib et al., 2008). Naughton et al. (2017) incorporated flood mechanisms such as backwatering of karstic sinks, overland flow from activated springs, and groundwater emergence in topographic low points which were originally developed using flood extents from a major flood in 2009 to improve hazard maps for a karstic limestone region of Ireland demonstrating that detailed knowledge of groundwater flood processes can improve the accuracy of groundwater flood mapping. The hydrogeological map developed by the British Geological Survey (Brisitsh Geological Survey, 2014) is currently used to highlight areas at greater risk of groundwater flooding. However, this dataset does not provide the detail that a local flood risk map would require. Specifically determining the depth of groundwater floods and the relative likelihood of groundwater emergence spatially are among the greatest challenges to mapping groundwater flooding (Cobby et al., 2009). Hughes et al. (2011) demonstrated that incorporating the local knowledge from landowners of groundwater emergence and flood frequency can be a critically important contribution to the development of localised groundwater flood maps. Due to the clear and present need for detailed local groundwater flood risk maps, a focus in their development could be one of the most useful research areas for decision makers. This would allow for better preparation for potential floods and enable infrastructural improvements (e.g., to sewer systems) in areas often affected by groundwater floods (Macdonald et al., 2012).

SHETRAN was favoured for the modelling section of this study because of its capability to represent complex aquifer processes and groundwater-surface water and groundwater-channel processes. One of the main limitations of the use of the SHETRAN model to represent NFM in the Test catchment was the 1km spatial resolution which made the representation of storage ponds and other catchment storage methods challenging. As a result, catchment storage enhancing NFM methods are not represented in this research. Future research should be directed at understanding the potential benefits of storage ponds within groundwater-dominated catchments. Reducing the catchment area to allow for a finer grid resolution to be applied could achieve this. The catchment-scale model can be maintained by adding an integrated local grid refinement (Haque et al., 2021). Although they are most often used within the SHETRAN model to increase the detail of groundwater-surface water dynamics in local areas (Haque et al., 2021), it could also be used to add detail (and topographic low points) in the digital elevation model. Regardless of the method used, it is recommended that this current gap in the NFM evidence base is addressed.

Changes in soil hydraulic properties generated through changing land management practices have not been included as part of the NFM interventions in these SHETRAN models. O'Connell et al. (2007) demonstrates that reversing the soil degradation and compaction caused by post-war agricultural intensification through land management practices such as cover crops, reduced stocking densities, and reduced tillage (and restricting the times of year that heavy machinery is used on soils) can increase soil water storage and other soil hydraulic properties. Furthermore, the relationship between soil hydraulic properties and subsequent infiltration rates have been shown to be a major determinant of flood response in groundwater dominated catchments (Ascott et al., 2017; Barnsley et al., 2021; Price, 1998). Given that soil hydraulic properties can be altered via land management practices, it follows that this could be used as a tool to alter infiltration into the bedrock affecting groundwater flood processes. Some initial simple soil change models were run to explore this concept.

The main changes in farming and land management practices currently come from agri-environment schemes in which farmers and landowners are granted economic incentives for managing their land in a way that aligns with the Government's environmental goals. At the time of analysis, the main schemes currently in use are the Countryside Stewardship Scheme (CS), the Entry Level Management Scheme, and the Higher-Level Management Scheme. Entry Level and Higher-Level schemes are tailor-made for each site and are varied. They range from no till, organic farming, using cover crops, protecting historical sites, and contributing to environmental education. Countryside Stewardship schemes are far more prescribed. Land managers agree to abide by a set of criteria to qualify to receive the subsidy - namely cover cropping, reduced stock densities and seasonal use of heavy machinery (reducing compaction). CS schemes are more suitable for generalisation and were therefore used as the basis for modelling.

Since the Environment Act 2021, three new environmental land management schemes have been introduced which will be piloted throughout 2022:

1) The Sustainable Farming incentive which pays farmers to manage their land in an environmentally sustainable way based on features such as hedgerows and grassland. This scheme offers greater flexibility to farmers by allowing farmers to choose the standards to apply, and where on the land to apply them.
2) The Local Nature Recovery scheme pays for actions which support local nature recovery, encouraging collaborative relationships between farmers to unify the landscape to aid nature in a natural recovery.
3) The Landscape Recovery scheme supporting landscape and ecosystem recovery by focusing on restoration schemes where appropriate, large scale tree planting, and peatland and salt marsh restoration.

It is expected that these environmental land management schemes will become the predominant incentive structures to promote environmentally sensitive farm and soil management. However, given that they are currently being piloted, there was no data on their location and implementation at the time of analysis and they have therefore not been used.

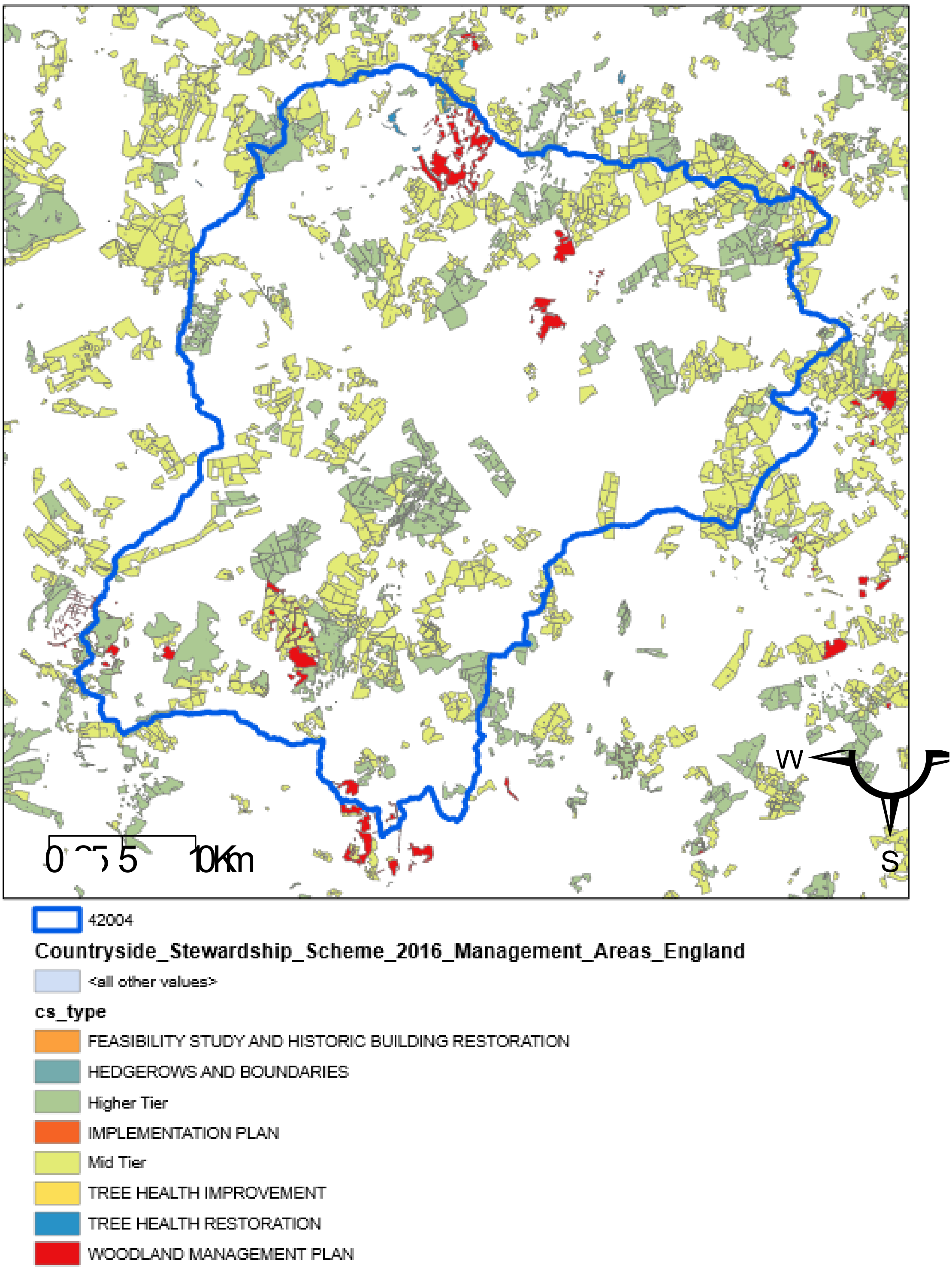


Figure 40 Countryside Stewardship schemes located in the Test catchment. This map is courtesy of the Environment Agency.

These simple soil simulations focused on changes to soils that can be generated through land management practices, namely soil bulk density (the number of available pore spaces or compression of the soil) and soil organic content (the percentage of soil made up of organic matter such as plant and animal detritus in various stages of decomposition). Soil saturated hydraulic conductivity (Ksat), which quantifies the ability of a soil to transmit water, is used here to approximate structural soil changes due to alterations in soil organic content and bulk density (Carof et al., 2007). Ksat was chosen because it is one of the key soil parameters in SHETRAN (Lewis et al., 2018). The literature shows that changes due to no or reduced tillage and winter cover crops can increase the Ksat in the top 10cm of soil by approximately 10% (Bodner et al., 2008; Skaalsveen et al., 2019). Winter cover crops are a basic requirement of the CS schemes, so a 10% increase in soil Ksat for all areas covered by a mid or higher tier CS scheme was applied (Figure 41).

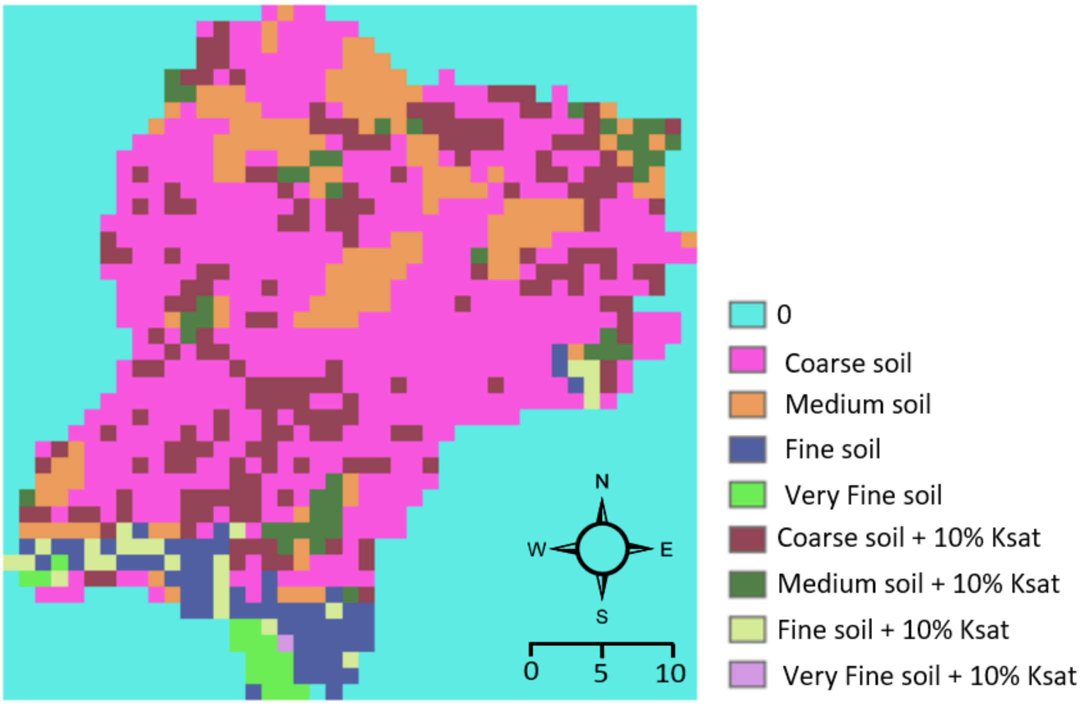


Figure 41 New SHETRAN soil input raster after soil saturated hydraulic conductivity has been increased by 10% in areas of Countryside Stewardship schemes. This generated four new soil classes.

A new SHETRAN soil input map was generated by reclassing soils in areas which intersected with a Countryside Stewardship scheme (Figure 42). This generated an additional four soil types where the parameters were altered by increased Ksat by 10% in the top layer of soils. All other soil parameters remained the same as originally prescribed in the pre-restoration (or baseline) scenario (Section 5.2.3.2.1, Table 15). All sub-soil parameters below the top layer were kept the same as the baseline scenario parameters. For the soil changes scenario, all other SHETRAN parameters were kept the same as the baseline scenario, with the addition of the updated soil input map. This altered soil scenario was then compared to the previous NFM scenarios (A1-B6).

Figure 43 shows that flood duration is significantly lower in the scenarios where soil properties have been changed to increase saturated hydraulic conductivity. For these scenarios, all the gauges had their maximum flood durations drop significantly from over 80 days to less than 20. Such a significant drop would certainly reduce disruptions from long duration floods in groundwater-dominated systems and are outside the range of uncertainty. As shown in Figure 44, the flood reduction potential at all four gauges is greater than was observed in Chapter 5. Maximum peak flood reductions were measured at 18%, 9%, 15%, and 30% at the Fishlake Meadows, Anton, Chilbolton, and Weston Colley gauges respectively. Whilst soil management scenarios generated the greatest simulated flood peak reductions compared to the baseline, they also generated major increases in some flood peaks. This was most notable at the Anton and Chilbolton gauges (Figure 44).

There are many flaws in these initial simulations in SHETRAN. A blanket 10% increase in Ksat is unlikely to be an accurate or achievable reduction in the Test catchment. Particularly as a majority of landowners are participating in government land management schemes and soils are assumed to be in relatively good condition. This makes an assumed 10% contrast in ksat before and after soil improvement schemes unlikely. The impact in soil structure due to changes in land management also vary depending on soil types. Furthermore, Ksat is a very simple approximation of the potential changes in soil properties that may be achieved through modifying land management practices.

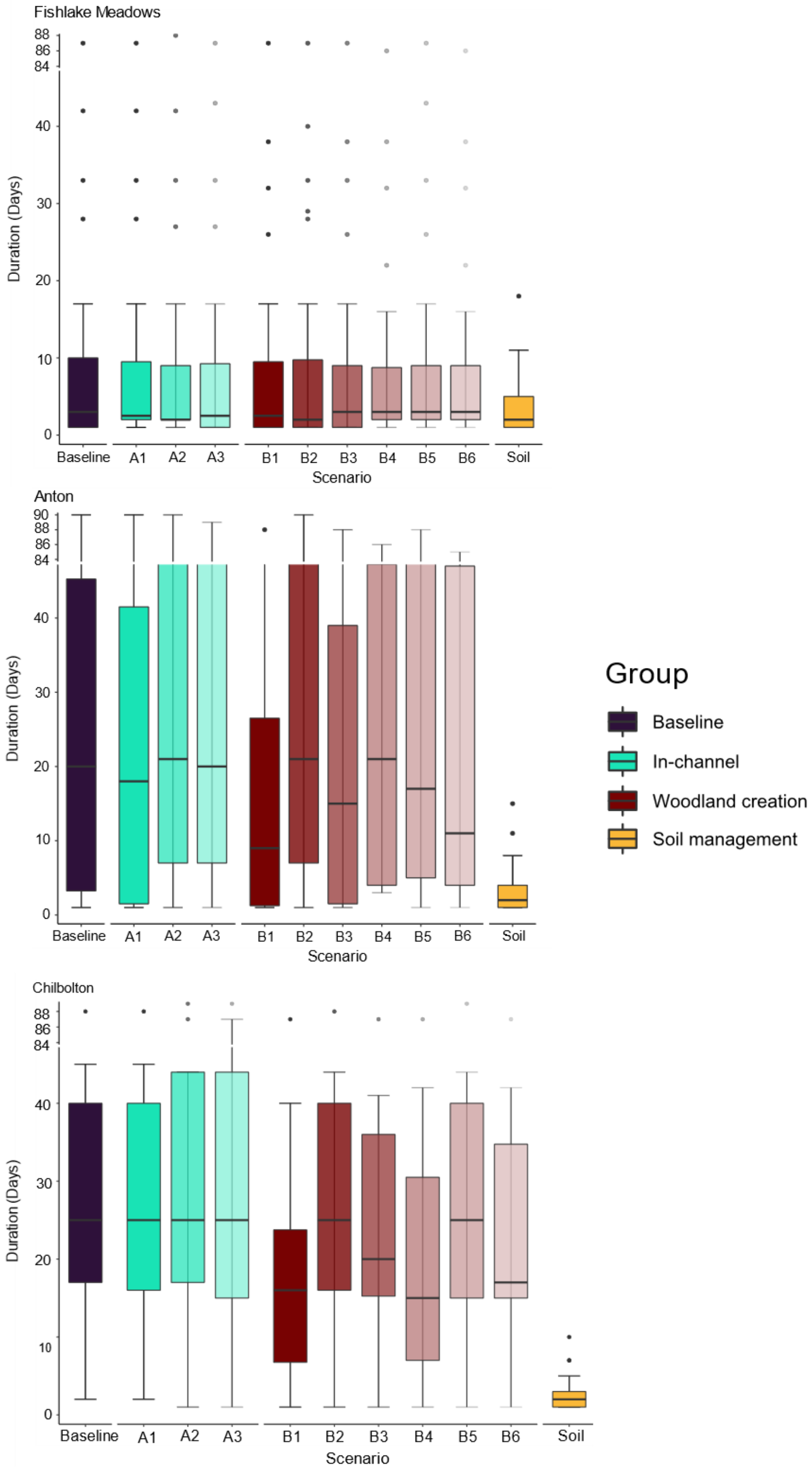


Figure 42 Flood duration boxplots comparing the results on the previous river restoration and increases in woodland area NFM scenarios and the initial soil management NFM scenario. These are all compared to a non-NFM baseline.

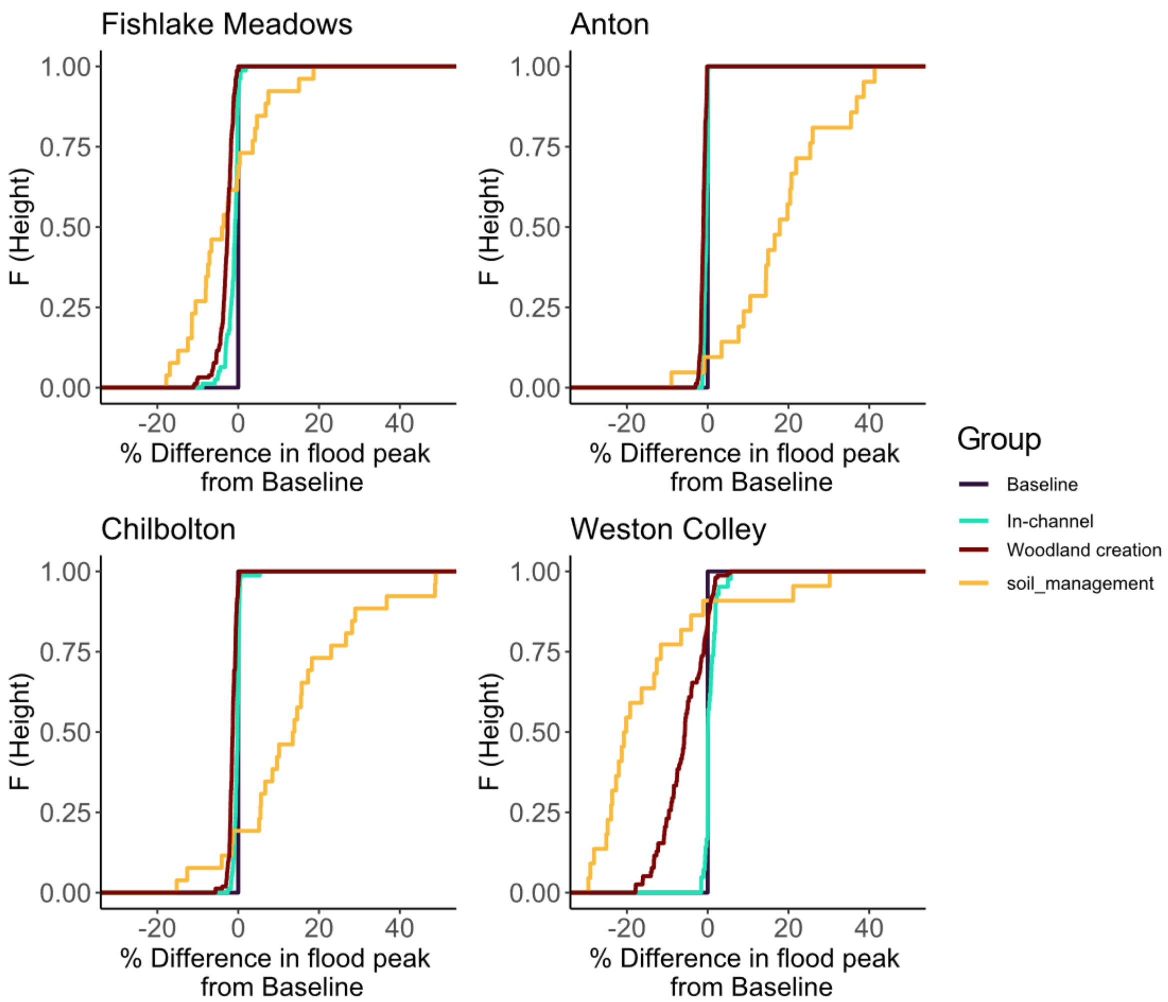


Figure 43 ECDF plot comparing the soil management scenario to the original in-channel river restoration and increased are of woodland scenarios.

Research from the LANDWISE research group is focusing on modelling the potential flood benefits that can be achieved in a chalk catchment (the Upper Thames) by altering land management practices to promote good soil conditions. At the time of writing, this research is unpublished but was presented as part of the NERC NFM webinar series by Badjana, Verhoef and Jennings with a presentation entitled ‘Modelling NFM in lowland catchments’ (NERC, 2020). Their research focuses on detailed field-based soil structure studies which are then used to parameterise and build a detailed soil hydraulics model. This combined field work and modelling approach found that using soil management methods that promote good soil health can change the soil hydraulic properties, with differing effects for different soil types. The soil hydraulic properties form this modelling and field work study were then used to parameterise the SWAT model. Preliminary model outputs showed a maximum flood peak reduction of 56% with a median of 26%. These results are comparable to those found in the initial model outputs from the soil management SHETRAN scenarios.

Both modelling studies are in early development phases but provide a key indication that maintaining and restoring healthy soils via environmental land management schemes could be key to reducing flood risk in permeable catchments. The results are indicative of significant potential benefits in chalk catchments by altering soil hydraulic properties through land management methods such as reduced stocking densities and cover cropping. This is further supported by the findings by Barnsley et al. (2021) which demonstrated that the permeability of soils and superficial deposits were a key indicator of hydrological response in chalk catchments. Moreover, the regulatory and funding infrastructure to implement such changes on a large scale are already in place. The Environmental Land Management and Countryside Stewardship schemes have already been in place for the past 20 years. These have now been superseded by the Sustainable Farming Incentive, the Local Nature Recovery scheme, and the Landscape Recovery scheme (Environment Act, 2021), all of which provide landowners and farmers greater flexibility and autonomy when accessing funding and support implementing the schemes. This is likely to generate greater uptake of such schemes, generating greater benefits to soils health and a potentially significant reduction in flood risk (particularly in permeable chalk catchments. This is certainly an area of research that requires significant investigation and future research. If such large reductions in flood peaks (and potentially flood durations) are observed in future groundwater-dominated catchment modelling and field studies, land management methods could become the key tool for flood reduction in chalk catchments.

Chapter 8 Conclusions

There is an incentive for decision makers and governing bodies to implement NFM schemes (Bark et al., 2021) because natural ways of managing catchments are encouraged and required by lawmakers and initiatives (DEFRA, 2004; Environment Act, 2021; Pitt, 2008). It is therefore crucial to ascertain the potential benefits of applying NFM in all scenarios. This research is directed at understanding the potential benefits of applying NFM in chalk groundwater dominated catchments. Key findings are in bold, followed by a summary of supporting evidence.

8.1 Key findings

- **Most chalk catchments in England are likely to have sub-optimal flood reductions (compared to the current evidence base) due to physical catchment characteristics and associated flood processes.**

A typology of 198 chalk catchments in England was generated and three classes were identified: 1) large chalk catchments (>108 km^2), 2) headwater catchments with permeable soils, and 3) catchments with impermeable soils and surfaces (urban and suburban land uses). Impermeable catchments are most suited to NFM due to a wider variety of flow pathways but only 56 of the 198 catchments included in the study were in this category. The literature suggests that natural flood management application is most effective for catchments <20 km^2, reducing the likelihood of significant flood mitigation in large catchments. NFM is also less likely to be effective in catchments with permeable soils due to greater rates of infiltration and groundwater recharge meaning a greater proportion of catchment water transfer occurs below the ground surface and less surface runoff is available for interception by natural flood management measures.

- **Increasing tree cover, revegetating river channels, and installing large woody debris can generate a flood peak reduction averaging 5%. However, this 5% flood peak reduction does not translate to a reduction in flood duration, meaning that flooding in groundwater catchments will likely remain highly disruptive despite NFM intervention.**

In groundwater dominated systems water tables rise slowly and floods onset gradually meaning that groundwater-dominated floods rarely pose a threat to human life. However, flood waters recede at the rate of the water table falling, causing long duration floods (lasting weeks or months). This can cause major disruptions due to prolonged closure of submerged transport infrastructure, incapacity of sewer systems, basement flooding and flooding of private property. Therefore, if NFM cannot reduce flood duration, as well as flood peaks, it is of limited applicable use within these types of catchments. Results from the SHETRAN scenarios show that an average 5% flood peak reduction is achieved at all river gauges situated within the Test catchment. Similar studies in catchments not dominated by groundwater processes found flood peak reductions of 30%. The greatest flood peak reduction of 14% was measured at the Weston Colley gauge, the smallest catchment in the study (54 Km^2). Although reductions in flood duration were generated under increased tree cover scenarios, they were all within the uncertainty boundaries of the model. It can therefore be concluded that these reductions in flood peak do not translate to reductions in flood duration. This is important for understanding the applicability of NFM in groundwater catchments. Therefore, implementation of NFM interventions will reduce the flood peak but is unlikely to meaningfully reduce the severity or duration of disruptions caused by groundwater flooding.

- **Increased catchment tree cover generated a greater flood response than in-channel interventions. A greater proportion of tree cover generates greater flood benefits. Applying the scale of tree cover that is required to generate flood benefits in practice is**

difficult due to trade-offs with other chalk catchment requirements, such as public water supply and space for farming practices.

Afforestation has demonstrated some success in generating flood benefits in groundwater-dominated chalk catchments. The Weston Colley sub catchment had the greatest peak flow reductions. However, due to a lack of available data, the impact of 14% peak flow reduction on the flood duration is unknown making it difficult to comment on the overall success of NFM schemes at this gauge and at this scale. Even so, the characteristics of this catchment as the smallest catchment with the smallest river channels and large amounts of simulated afforestation distributed relatively evenly corresponding to a reduction in flood peak agrees with the literature on the conditions for optimum flood benefit from afforestation. Furthermore, as seen in Chapter 5, increasing tree cover in all sub-catchments of the river test resulted in an average flood peak reduction of 5%, demonstrating that afforestation has a flood reduction effect in chalk catchments. To a produce a sufficient flood benefit from afforestation there are significant trade-offs. Large quantities of land are required to be converted to woodland to generate these changes (45% coverage distributed throughout the catchments in the case of the Weston Colley Gauge). There are also concerns about how the storage and evapotranspiration processes which are advantageous during times of flood risk may further exacerbate low flows.

- **Under future projected climate changes, NFM maintains its effect when compared to non-NFM baseline scenarios. This equates to an average 5% flood peak reduction and insignificant reductions in flood duration. Under the more severe rainfall scenarios, floods were simulated to last up to 200 days, representing severe disruptions and damages.**

Moderate reductions in peak flow (average 5%) are maintained for all, including the most extreme, climate projections compared to a non-NFM scenario. This demonstrates that a significant increase in tree coverage and river channel restoration could maintain moderate benefits under all UKCP18 climate scenarios for up to 80 years. These modest peak flow reductions do not translate into reductions in flood duration that are measurable beyond the range of uncertainty. This is a major shortfall for NFM function in the future, as simulations from future climate scenarios project extremely long flood durations for both RCP2.6 and 8.5 at the 90th percentile probability, suggesting that moderate peak flow reductions are inadequate to reduce major disruptions caused by simulated floods. These small benefits could be used as an adaptation strategy to support the resilience of other hard engineering flood management approaches in the future. Because the benefits of NFM are mild, other future climate change pressures on chalk streams, such as seasonal nitrate pollution, pressure on public water supply, and ecological homogenisation due to increased variation in the annual flow regime may take priority for the financial investment required for climate change adaptation strategies. Tackling these issues will require cross-disciplinary research and discussions.

- **Due to a limited overall effect of NFM (increases in woodland are and in-channel interventions) on flood reduction, it is suggested that the main benefit of implementing NFM in chalk catchments are the ecological benefits.**

The results from all flood model scenarios indicate that NFM has a limited flood reduction effect in chalk catchments. Limited flood benefits were observed at the larger sub-catchment gauges for all the in-channel NFM intervention scenarios. At the headwater catchment, Weston Colley, some increased flood peaks (and assumed bank overtopping) were observed because of in-channel interventions, but reduced conveyance that may have occurred as a result of this effect was not measurable downstream. Whilst reductions in peak flood were observed for scenarios where the woodland area was increased, the scale of woodland coverage required to achieve these benefits is unrealistic for practical application. For all scenarios, reductions to flood duration were within the range of model uncertainty meaning there were no observable changes to flood duration. These findings persist for climate change scenarios. It is therefore suggested that measures which can be categorised as in-channel measures (Large Woody Debris in the river channel, re vegetating river channel and banks, reduced weed cutting regimes) and increasing catchment woodland areas be implemented predominantly for their ecological benefits and restorative purposes because the flood benefits derived from them are minimal. There is academic consensus on the positive benefits of NFM on ecology, biodiversity, soil health, and water quality with these advantages being well documented within the literature.

8.2 Summary

All together these findings suggest that NFM has a reduced flood reduction impact in chalk groundwater catchments compared to non-groundwater dominated catchments. The SHETRAN models indicate that one of the most effective strategies could be to increase the proportion of catchment tree cover. In-channel measures, particularly river channel restoration efforts should be completed for the ecological gains rather than flood reduction because flood reduction benefits have been shown to be minimal. This is important as flood reduction has previously been part of the justification for completing these types of projects on the Rivers Test and Itchen. In-channel and woodland creation for NFM has also been shown to have limited capacity to reduce flood impacts under future projected climate changes within the next 80 years. Hard engineering is likely to be required in the near future to avoid prolonged flood disruption, particularly in updating or increasing the resilience of sub-surface infrastructure to groundwater flooding. Given that there are multiple other decisive pressures on the chalk stream environment, including the stability and quality of public water supply, it may be more pertinent to allocate climate adaptation strategy resources in those directions, given that the benefits of NFM are moderate.

It is also suggested that NFM interventions be focused locally on known sources of surface water flood flows, such as springs and winterbournes which are active when the water tables and flood risk is high. Catchment storage and flood conveyance reducing NFM strategies could be used in this scenario. However, this application of NFM has not been empirically tested and is therefore predominantly suggested as an area for future research. It is known that there is current decision maker interest in this approach. To effectively research or apply this approach, a more detailed local understanding of groundwater emergence is required, including groundwater emergence depth and flow rate from hydrogeological features. More detailed flood maps are a crucially required resource for flood planning.

Initial modelling from this research and from the LANDWISE research project suggest that increasing soil health by improving land management strategies could generate flood benefits. Preliminary model runs from this study indicate that a 10% increase in saturated hydraulic conductivity of soils (the rate at which soils transmits water through it) over a large area of the catchment could significantly reduce flood durations, reducing disruption from prolonged floods, as well as providing a flood peak reduction. Because of the potential for soil management strategies as an effective flood mitigation tool, it is suggested that this be the main area of future research for the application of NFM in chalk catchments.

Appendix A Catchments in their groups after Redundancy Analysis

Group 1 - Large Catchments					
No.	**Station Number**	**River**	**Location**	**Catchment Area (km^2)**	**Alternative group where classification is uncertain**
1	26001	West Beck	Wansford Bridge	195.56	
2	26002	Hull	Hempholme Lock	397.23	
3	26004	Gypsey Race	Bridlington	257.15	
4	26005	Gypsey Race	Boynton	248.13	2
5	26009	West Beck	Snakeholme Lock	195.61	
6	27087	Derwent	Low Marishes	475.93	
7	33003	Cam	Bossington	807.32	
8	33004	Lark	Isleham	464.16	
9	33006	Wissey	Northwold Total	259.36	
10	33007	Nar	Marham	147.39	
11	33013	Sapiston	Rectory Bridge	196.16	
12	33014	Lark	Temple	274.04	
13	33016	Cam	Jesus Lock	769.19	
14	33019	Thet	Melford Bridge	311.38	
15	33021	Rhee	Burnt Mill	308.05	
16	33022	Ivel	Blunham	539.63	
17	33023	Lea Brook	Beck Bridge	131.89	3
18	33024	Cam	Dernford	199.59	

19	33028	Flit	Shefford	119.42	
20	33034	Little Ouse	Abbey Heath	707.76	
21	33044	Thet	Bridgham	274.99	
22	33057	Ouzel	Leighton Buzzrad	122.40	
23	34003	Bure	Ingworth	161.27	
24	34004	Wensum	Costessey Mill	559.70	
25	34006	Waveney	Needham Mill	376.08	
26	34011	Wensum	Fakenham	162.93	2
27	34014	Wensum	Swantom Morely Total	377.46	
28	34019	Bure	Horstead Mill	327.91	
29	36001	Stour	Stratford St Mary	838.01	
30	36006	Stour	Langham	571.35	
31	36015	Stour	Lamarsh	481.28	3
32	38001	Lee	Feildes Weir	1045.10	
33	38018	Upper Lee	Water Hall	157.73	3
34	38031	Lee	Rye Bridge	758.52	
35	39003	Wandle	South Wimbledon	153.73	
36	39010	Colne	Denham	725.90	
37	39013	Colne	Berrygrove	349.25	3
38	39016	Kennet	Theale	1037.87	
39	39019	Lambourn	Shaw	235.43	
40	39023	Wye	Hedsor	134.18	2
41	39027	Pang	Pangbourne	175.68	
42	39030	Gade	Croxley Green	182.35	
43	39031	Lambourn	Welford	158.87	

44	39043	Kennet	Knighton	299.17	2
45	39078	Wey (North)	Farnham	192.60	2
46	39103	Kennet	Newbury	534.13	
47	39104	Mole	Esher	471.36	
48	39115	Pang	Bucklebury	108.94	
49	40003	Medway	Teston	1261.311	
50	40008	Great Stour	Wye	226.40	3
51	40011	Great Stour	Horton	341.27	
52	40012	Darent	Hawley	187.31	
53	40016	Cray	Crayford	123.49	2
54	40018	Darent	Lullington	122.24	2
55	41004	Ouse	Barcombe Mills	400.61	
56	41009	Rother	Hardham	360.77	
57	42010	Itchen	Highbridge & Allbrook Total	339.91	
58	42012	Anton	Fullerton	186.16	2
59	42016	Itchen	Easton	234.17	2
60	42024	Test	Chilbolton Total	478.43	
61	43003	Avon	East Mills Total	1459.44	
62	43004	Bourne	Laverstock	165.21	
63	43005	Avon	Amesbury	326.47	
64	43006	Nadder	Wilton	215.63	
65	43007	Stour	Throop	1062.09	
66	43008	Wylye	South Newton	448.17	
67	43018	Allen	Walford Mill	170.82	2
68	43024	Wylye	Stockton Park	170.89	2

69	44001	Frome	East Stoke Total	414.59	
70	44002	Piddle	Baggs Mill	183.80	
71	44004	Frome	Dorchester Total	205.67	

Group 2 - Catchments with more permeable soils					
No.	**Station Number**	**River**	**Location**	**Catchment Area (km^2)**	**Alternative group where classification is uncertain**
1	26003	Foston Beck	Foston Mill	59.59	
2	26006	Elmswell Beck	Little Driffield	133.18	1
3	26008	Mires Beck	North Cave	40.96	
4	26013	Driffield Trout	Driffield	53.34	
5	26016	Gypsey Race	Kirby Grindalythe	16.98	
6	27073	Brompton Beck	Snainton Ings	8.06	
7	29001	Waithe Beck	Brigsley	108.75	
8	29003	Lud	Louth	56.42	3
9	33025	Babingly	West Newton Mill	44.69	
10	33032	Heacham	Heacham	56.16	
11	33033	Hiz	Arlesey	112.96	
12	33040	Rhee	Ashwell	2.00	
13	33049	Stanford Water	Buckenham Tofts	46.45	
14	33052	Swaffham Lode	Swaffham Bulbeck	33.12	
15	33054	Babingley	Castle Rising	48.54	
16	33056	Quy Water	Lode	92.56	
17	33061	Shep	Fowlmere One	1.03	
18	33062	Guilden Brook	Fowlmere Two	3.40	
19	33064	Whaddon Brook	Whaddon	14.53	
20	33065	Hiz	Hitchin	12.03	
21	33068	Cheney Water	Gatley End	0.11	

22	34012	Burn	Burnham Overy	83.87	
23	34018	Stiffkey	Warham	86.13	3
24	38017	Mimram	Whitwell	38.40	
25	39015	Whitewater	Lodge Farm	46.99	
26	39029	Tilling Bourne	Shalford	58.78	
27	39032	Lambourn	East Shefford	145.06	1
28	39033	Winterbourne Stream	Bagnor	45.31	
29	39036	Law Brook	Albury	16.07	
30	39037	Kennet	Marlborough	136.43	1
31	39039	Wye	High Wycombe	67.73	
32	39061	Letcombe Brook	Letcombe Bassett	3.99	
33	39065	Ewelme Brook	Ewelme	11.98	
34	39077	Og	Marlborough Poulton Farm	63.95	
35	39091	Misbourne	Quarrendon Mill	65.87	
36	39101	Aldbourne	Ramsbury	53.09	
37	39102	Misbourne	Denham Lodge	93.24	
38	39107	Hogsmill	Ewell	8.44	
39	39112	Letcombe Brook	Arabellas Lake	3.10	
40	39113	Manor Farm Brook	Letcombe Regis	1.38	
41	39114	Pang	Frilsham	90.06	
42	39118	Wey	Alton	44.50	
43	39119	Wey	Kings Pond (Alton)	46.15	
44	39120	Caker Stream	Alton	83.94	

45	39146	Mill Brook	Blewbury	2.01	
46	39147	Wendover Springs	Wendover	9.49	
47	40013	Darent	Otford	98.19	
48	40014	Wingham	Durlock	30.72	
49	40033	Dour	Crabble Mill	44.93	
50	41015	Ems	Westbourne	57.89	
51	41023	Lavant	Graylingwell	86.20	
52	41033	Costers Brook	Cocking	2.74	
53	41034	Ems	Walderton	42.46	
54	41037	Winterbourne Stream	Lewes	17.48	
55	42005	Wallop Brook	Broughton	53.46	
56	42006	Meon	Mislingford	75.84	
57	42007	Alre	Drove Lane Alresford	57.45	
58	42008	Cheriton Stream	Sewards Bridge	74.33	
59	42009	Candover Stream	Borough Bridge	72.06	
60	42015	Dever	Weston Colley	50.15	
61	42025	Lavant Stream	Leigh Park	55.96	
62	42026	Wallop Brook	Bossington	61.13	
63	42027	Dever	Bransbury	122.36	1
64	43010	Allen	Loverley Farm	94.84	
65	43011	Ebble	Bodenham	105.55	
66	43012	Wylye	Norton Bavant	114.01	1
67	43014	East Avon	Upavon	85.82	

68	44006	Sydling Water	Sydling St Nicholas	12.05	
69	44008	South Winterbourne	Winterbourne Steepleton	20.18	3
70	44009	Wey	Broadwey	8.00	
71	101003	Lukely Brook	Carisbrooke Mill	14.86	

Group 3 - Catchments with less permeable soils					
No.	**Station Number**	**River**	**Location**	**Catchment Area (km^2)**	**Alternative group where classification is uncertain**
1	26007	Catchwater	Withernwick	10.84	
2	29002	Great Eau	Claythorpe Mill	80.42	
3	33011	Little Ouse	County Bridge Euston	129.34	
4	33027	Rhee	Wimpole	128.49	
5	33029	Stringside	Whitebridge	95.41	
6	33030	Clipstone Brook	Clipstone	40.35	
7	33045	Wittle	Quidenham	27.45	
8	33046	Thet	Redbridge	14.43	
9	33050	Snail	Fordham	57.88	
10	33051	Cam	Chesterford	140.02	
11	33053	Granta	Stapleford	113.98	
12	33055	Granta	Babraham	101.97	
13	33066	Granta	Linton	61.61	
14	33070	Lark	Fornham St Martin	111.07	
15	34001	Yare	Colney	228.81	
16	34002	Tas	Shotesham	153.19	
17	34005	Tud	Costessey Park	72.11	
18	36002	Glem	Glemsford	85.61	
19	36004	Chad Brook	Long Melford	50.33	
20	36005	Brett	Hadleigh	155.85	

21	36007	Belchamp Brook	Bardfield Bridge	58.16	
22	36008	Stour	Westmill	222.82	
23	36009	Brett	Cockfield	25.56	
24	36010	Bumpstead Brook	Broad Green	27.58	
25	36011	Stour Brook	Sturmer	34.24	
26	36012	Stour	Kedington	76.65	
27	36013	Brett	Higham	191.78	
28	37012	Colne	Poolstreet	64.49	
29	37016	Pant	Copford	63.80	
30	38002	Ash	Mardock	78.00	
31	38003	Mimram	Panshanger Park	130.21	
32	38004	Rib	Wadesmill	136.79	
33	38005	Ash	Easneye	84.65	
34	38006	Rib	Herts Training School	148.67	
35	38011	Mimram	Fulling Mill	99.25	
36	38012	Stevenage Brook	Bragbury Brook	35.11	
37	38013	Upper Lee	Luton Hoo	70.31	
38	38028	Stanstead Brook	Gypsy Lane	26.37	2
39	38029	Quin	Griggs Bridge	50.41	
40	38030	Beane	Hartham	173.85	
41	39004	Wandle	Beddington Park	117.35	2

42	39005	Beverly Brook	Wimbledon Common	39.49	
43	39012	Hogsmill	Kingston Upon Thames	72.91	
44	39014	Ver	Hansteads	134.55	
45	39028	Dun	Hungerford	100.09	
46	39055	Yeading Brook West	North Hillingdon	1.31	
47	39088	Chess	Rickmansworth	96.91	
48	39089	Gade	Bury Mill	44.73	
49	39125	Ver	Redbourn	62.58	
50	39127	Misbourne	Little Missenden	47.26	2
51	40015	White Drain	Fairbrook Farm	31.40	
52	40027	Sarre Pen	Calcott	19.59	
53	41003	Cuckmere	Sherman Bridge	130.33	
54	41028	Chess Stream	Chess Bridge	25.01	
55	42001	Wallington	North Fareham	111.68	
56	42011	Hamble	Frogmill	55.25	

Appendix B River Habitat-style survey used during field recces.

Estate: ______________________ River reach no.: ______ no. field photos taken:

Brief description:

General:

Complexity of reach (high, med, low)		Approx reach length		Channel width		Is channel wadeable	

Photo taken?

Artificial features:

Size of weir		If yes, is water impounded?		Culverts		Bridges	

Is channel realigned?

Is channel over-deepened?

Morphological features:

No. of pools		No .riffles		No. point bars		No. vegetated point bars	
Braided channel		Side channels		Debris dams		Marginal vegetation	
Bed material							

Meanders?

Clarity of water:

Appendix B

Bank profiles:

Natural/unmodified	L	R	Artificial/modified	L	R
Vertical/undercut			Resectioned (reprofiled)		
Vertical with toe			Reinforced - whole		
Steep (>45°)			Reinforced - top only		
Gentle			Reinforced - toe only		
Composite			Artificial two-stage		
Natural berm			Poached bank		
			Embanked		
			Set-back embankment		

Evidence of dredging?

Vegetation:

J EXTENT OF TREES AND ASSOCIATED FEATURES	*record even if <1%					
TREES (tick one box per bank)	Left	Right	**ASSOCIATED FEATURES** (tick one box per feature)	None	Present	E (≥33%)
None	❑	❑	Shading of channel	❑	❑	❑
Isolated/scattered	❑	❑	*Overhanging boughs	❑	❑	❑
Regularly spaced, single	❑	❑	*Exposed bankside roots	❑	❑	❑
Occasional clumps	❑	❑	*Underwater tree roots	❑	❑	❑
Semi-continuous	❑	❑	Fallen trees	❑	❑	❑
Continuous	❑	❑	Large woody debris	❑	❑	❑

Suitability to drone use:

Presence of trees - % cover		Approx distance from private property	

For this survey, river left and right are correct when facing downstream.

Footpath: left right Mowing: Left Right

Variety of riparian vegetation? (take a photo example):

Instream vegetation:

Marginal vegetation: Approx. width of margin:

Ranunculus - % cover (photo example):

Other vegetation – name and % cover:

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